Transverse Spin Results from STAR

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RHIC & AGS Annual Users' Meeting

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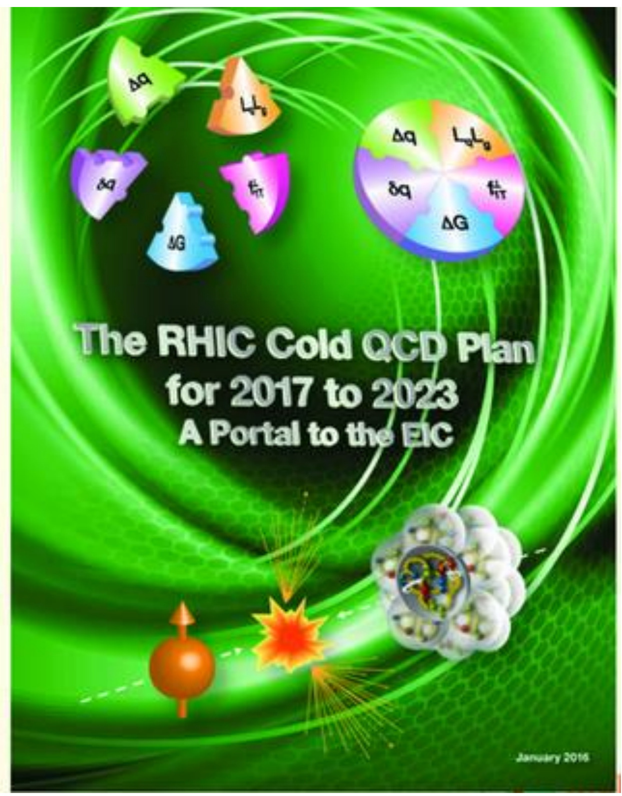
BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

arXiv: 1501.01220



arXiv:1602.03922

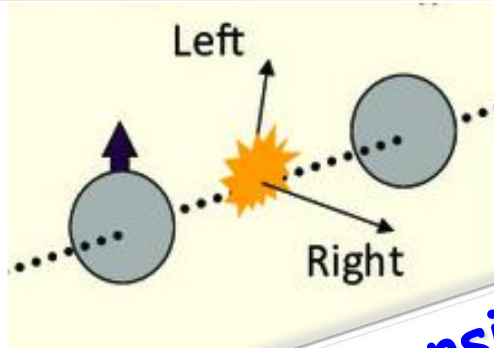
Plan of the talk

- ✧ Historical back ground and physics motivations
- ✧ New results
  - Initial state mechanism:
    - Sivers fcn through weak boson production
  - Final state mechanism:
    - Transversity through Collins in jets
    - Transversity through di-hadron IFF
  - nuclear TMDs and saturation effects in $p^{\uparrow}$+A
- ✧ Future Plans
  - Ultimate study of Sivers through Drell-Yan, weak bosons, photons
  - First look at the GPD Eg though $j/\psi \to e^{+}e^{-}$ in $p^{\uparrow}+p^{\uparrow}$
- ✧ Conclusions

The discovery of large asymmetries

Transverse single spin asymmetry

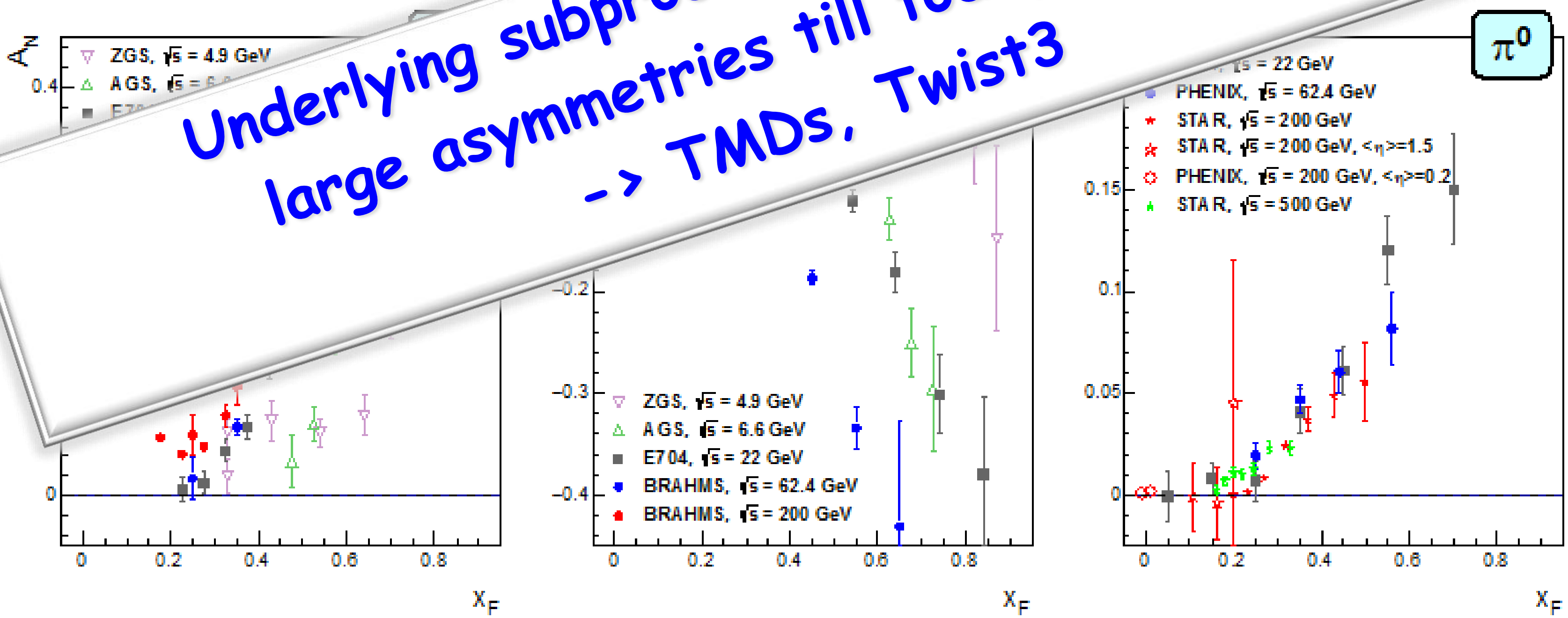
$$A_N \approx \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



Theory (A_N~10^{-4})
Expected to be small
[Kane, Pumplin, Repko, ... (1978)]

Exp...
...ab,
...r

Underlying subprocess responsible for the large asymmetries till today not clear
-> TMDs, Twist3



Surprise! **The asymmetries are nearly independent over a very wide range of √s**

Quantum tomography of the nucleons

Wigner distribution **5D**

$$W\left(x, k_T, r_T\right)$$

TMDs d^2r_T

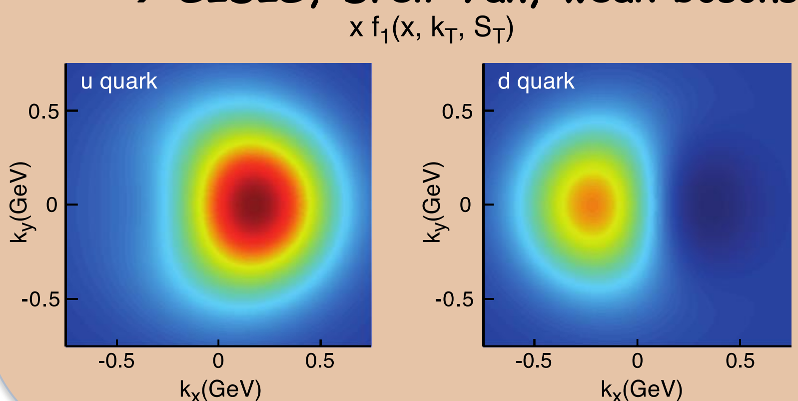
GPDs d^2k_T

3D

2D+1 picture in momentum space

transverse momentum dependent PDFs

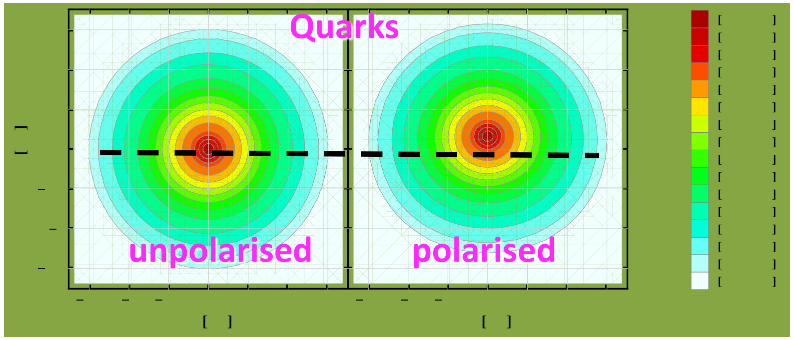
→ SIDIS, Drell-Yan, weak bosons



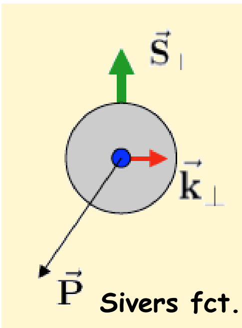
2D+1 picture in coordinate space

generalized parton distributions

→ exclusive reaction



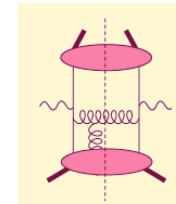
Motivations – Transverse Single Spin Asymmetry (A_N)



Transverse momentum dependent
$Q \gg Q_T >= \Lambda_{QCD}$
$Q \gg p_T$

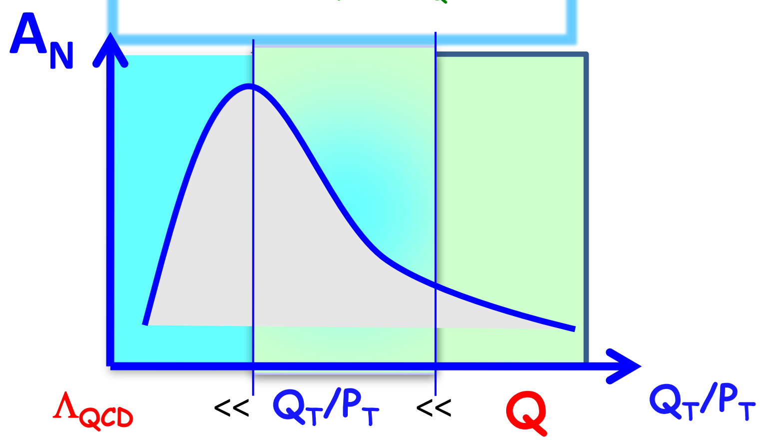
$$A_N \approx \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Collinear/ twist-3
$Q, Q_T \gg \Lambda_{QCD}$
$p_T \sim Q$



Efremov, Teryaev; Qiu, Sterman

Intermediate Q_T
$Q \gg Q_T/p_T \gg \Lambda_{QCD}$



TMDs
need 2 scales
Q^2 and p_t
Examples: DY, W/Z

Twist-3
needs only 1 scale
Q^2 or p_t
But
should be of reas. size.
Examples: $A_N(\pi^0/\gamma/\text{jet})$

related through

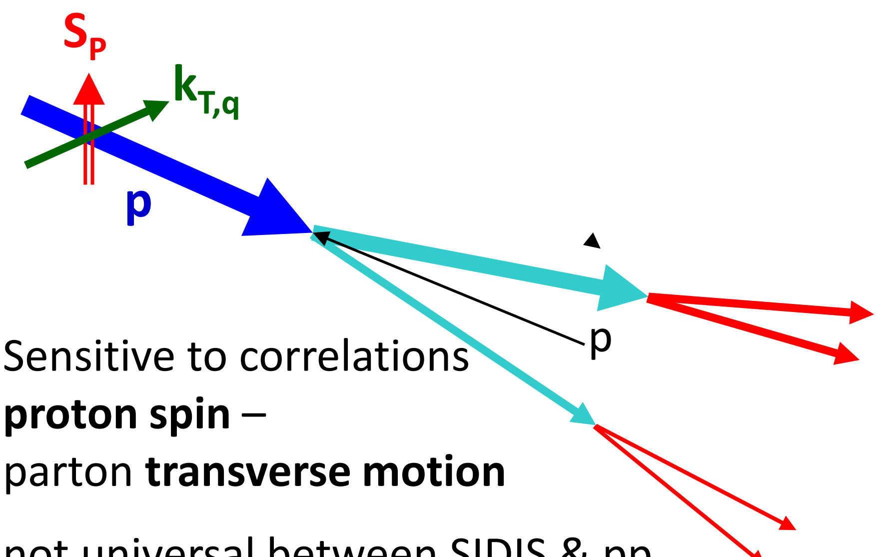
$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

How to study TMDs in p+p collisions

Initial State

SIVERS/Twist-3

- A_N as function of rapidity, E_T, p_T and x_F for inclusive jets, direct photons
- A_N for heavy flavour → gluon
- A_N as a function of rapidity, p_T for $W^{+/-}$, Z^0, DY



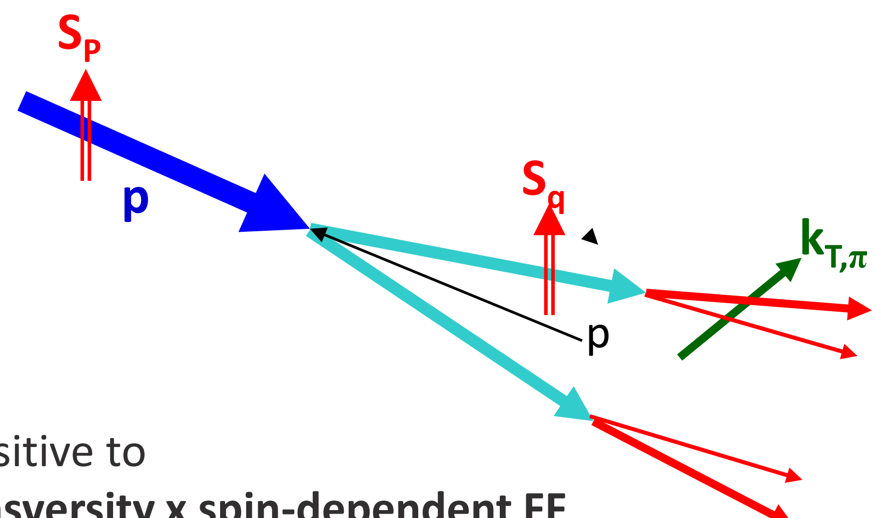
Sensitive to correlations **proton spin** – parton **transverse motion**

not universal between SIDIS & pp

Final State

Collins Mechanism

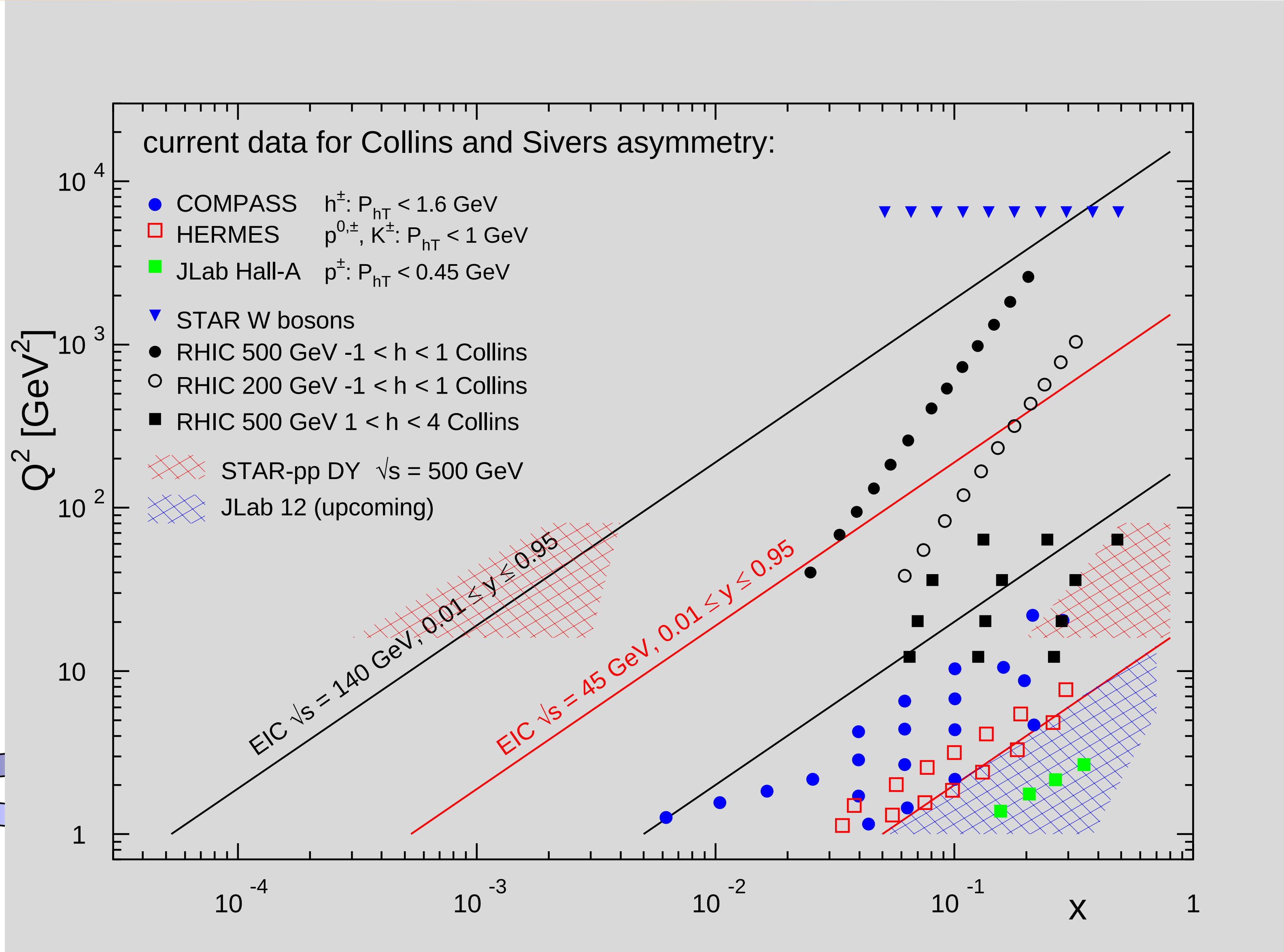
- asymmetry in jet fragmentation
  - **$\pi^{+/-}\pi^0$ azimuthal distribution in jets**
  - **Interference fragmentation function**
- A_N for pions
  → Novel Twist-3 FF Mechanisms



Sensitive to **transversity x spin-dependent FF**

universal between SIDIS & pp & e+e-

RHIC – a unique opportunity!



Test the TMD evolution and factorization

Different PDFs and FF can follow different evolution concepts

Evolution of 1d PDFs ≠ evolution of TMDs ≠ evolution of Twist-3

TMD evolution can be tested at RHIC

→measurements of TMD observables for DY and W/Z

→measurements of TMD observables for √s: 200 & 500 GeV at fixed x_T

TMDs and factorization

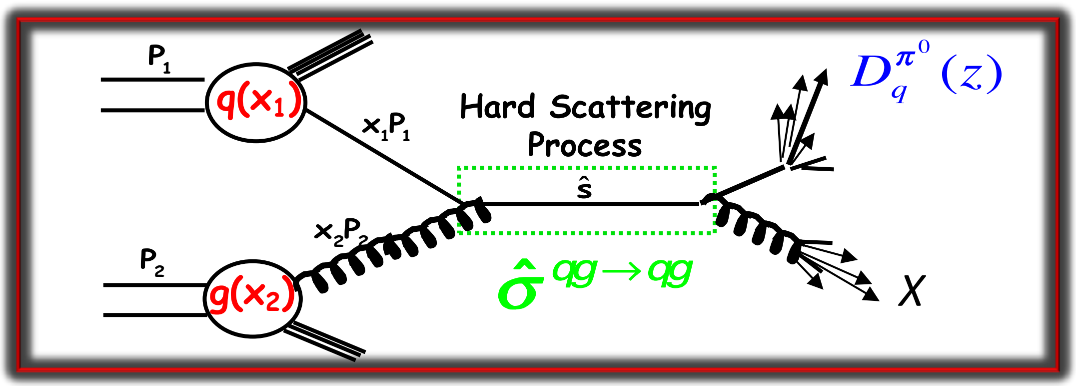
$\sigma(pp \to \pi^0 X) \sim q(x_1) + g(x_2) + \sigma^{qg\to qg} + D^{\pi^0}(z)$

Partonic hard scattering cross section → calculable in pQCD (process dependent)

Parton distribution functions (need experimental input)

Fragmentation functions (need experimental input)

Universal non-perturbative functions



When color flow is in too many directions:

factorization breaking

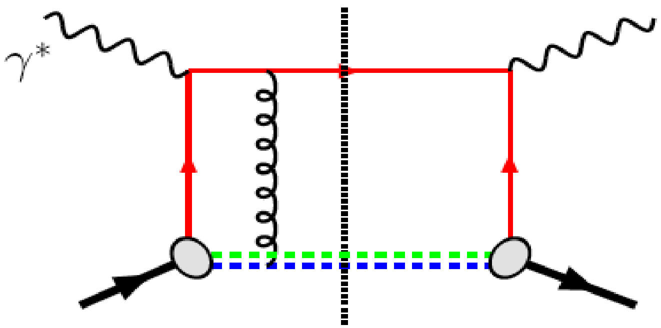
[Collins & J. Qiu '07; Collins '07; Rogers & Mulders '10]

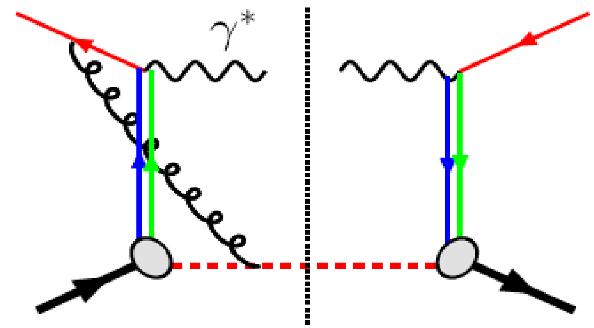
Test the non-Universality of the Sivers function

QCD:

DIS: γq scattering
attractive FSI

pp: $q/\bar{q}$ annihilation
repulsive ISI





$$\text{Sivers}_{\text{DIS}} = - \text{ Sivers (DY or W or Z)}$$

The sign change of the Sivers function

a fundamental prediction from the gauge invariance of QCD

Experimental test is critical test for our understanding of TMD's and TMD factorization → No sign-change? We have to rethink factorization!

Test through Drell-Yan process: COMPASS (CERN), proposed SeaQuest (FermiLab)

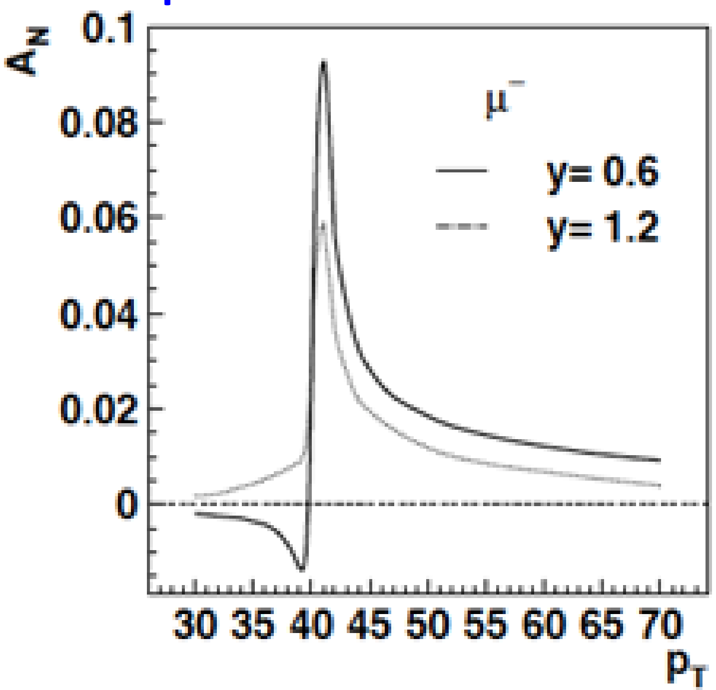
- Needs strong background suppression, high lumi
- @ STAR in run 2017(PostShower upgrade)

Polar. weak boson production (only at RHIC)

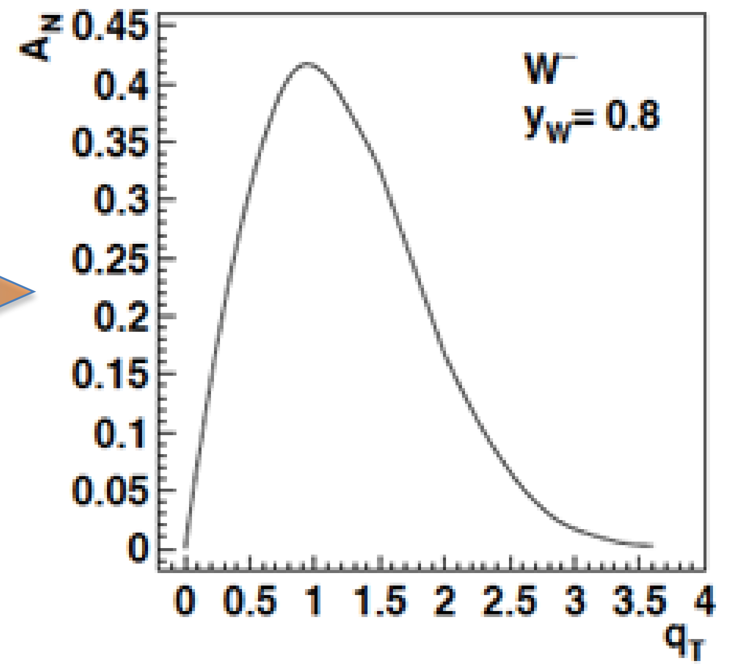
- Very low background
- Very high Q^2-scale (~ W/Z boson mass)

A_N for weak bosons

Lepton's transverse momentum



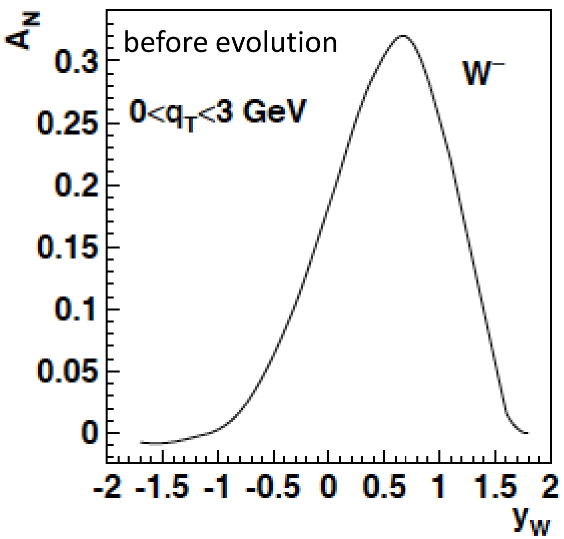
Boson's transverse momentum



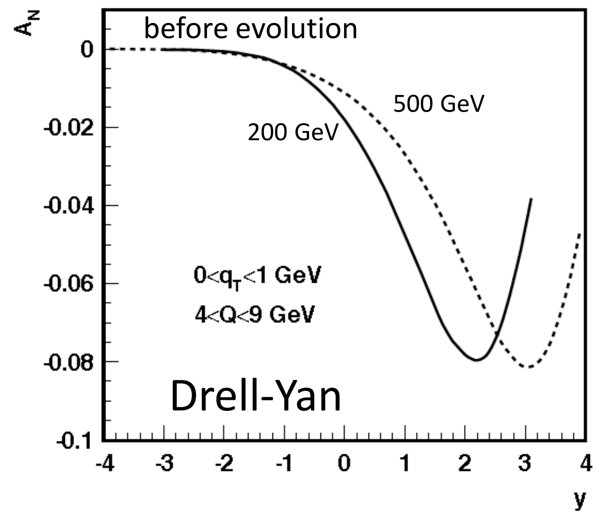
- Asymmetry from lepton-decay is small → Full kin. reconstruction of the boson needed
  - > Z^0 easy to reconstruct (but small cross-section)
  - > W kin. can be reconstructed from the hadronic recoil (first time at STAR)

The TMD evolution & sea-quarks Sivers

Z.-B. Kang & J.-W. Qui arXiv:0903.3629



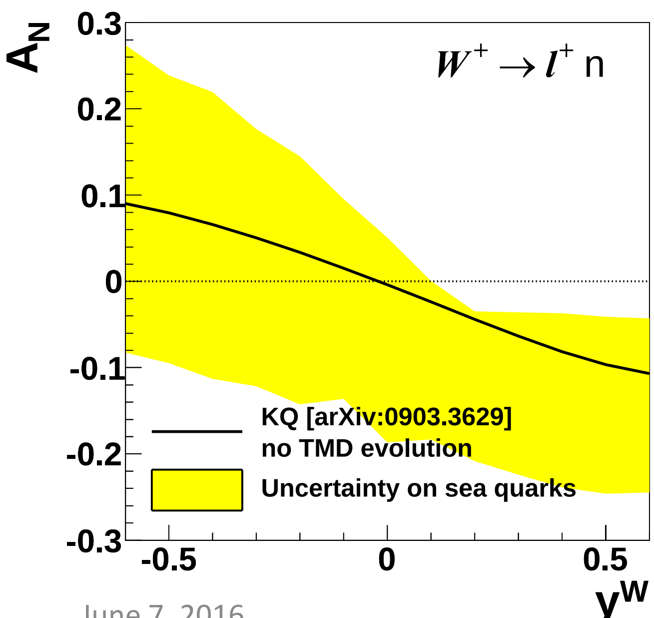
Z.-B. Kang & J.-W. Qui Phys.Rev.D81:054020,2010



- **Size of the TMD evolution effect still under discussion in theory community**

For details see

J. Collins, T. Rogers, Phys.Rev. D91 (2015) 7, 074020

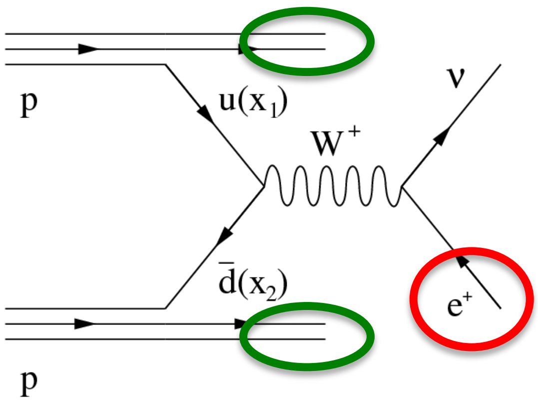


- **What is the sea-quark Sivers fct.?**
  - → ***Sea quarks are mostly unconstrained from existing SIDIS data... but* they can give a relevant contribution!**
  - → W's ideal → rapidity dependence of A_N separates quarks from antiquarks

$W^{\pm}$ data can constrain the sea-quark Sivers function

RECENT EXPERIMNTAL RESULTS

Measurement of TSSA for weak bosons @ STAR



Ingredients for the analysis

- Isolated electron
- neutrino (not measured directly)
- Hadronic recoil

W boson momentum reconstruction technique well tested at FermiLab and LHC

[CDF: PRD 70, 032004 (2004); ATLAS: JHEP 1012 (2010) 060]

Phys. Rev. Lett. 116, 132301 (2016)
Editor's suggestion
[arXiv:1511.06003]

World's first direct experimental test of the sign change in the Sivers function

- **RHIC is the only polarized p+p collider.** Its top energy is enough to produce weak bosons
- **Selection of weak bosons well established at STAR**
  - **Long. spin asymmetries:**
    Phys. Rev. Lett. 113, 072301 (2014)
    Phys. Rev. Lett. 106, 062002 (2011)
  - **unpolarized xsec:**
    Phys. Rev. D 85, 092010 (2012)
- **STAR's first attempt to reconstruct the produced boson's kinematics**

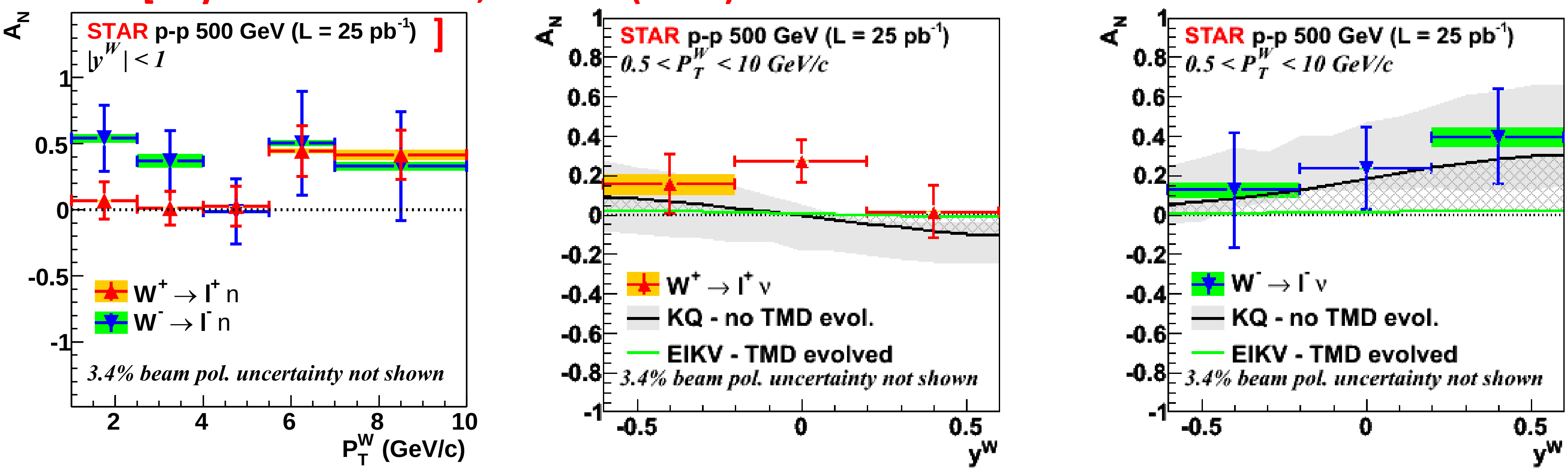
A_N vs W-rapidity

We use the "left-right" formula to cancel dependencies on geometry and luminosity

$$A_N \approx \frac{1}{P}\frac{\sqrt{N_R^{\uparrow} N_L^{\downarrow}} - \sqrt{N_L^{\uparrow} N_R^{\downarrow}}}{\sqrt{N_R^{\uparrow} N_L^{\downarrow}} + \sqrt{N_L^{\uparrow} N_R^{\downarrow}}}$$

Average RHIC polarization
(p+p run 2011 tran.)
<P> = 53%

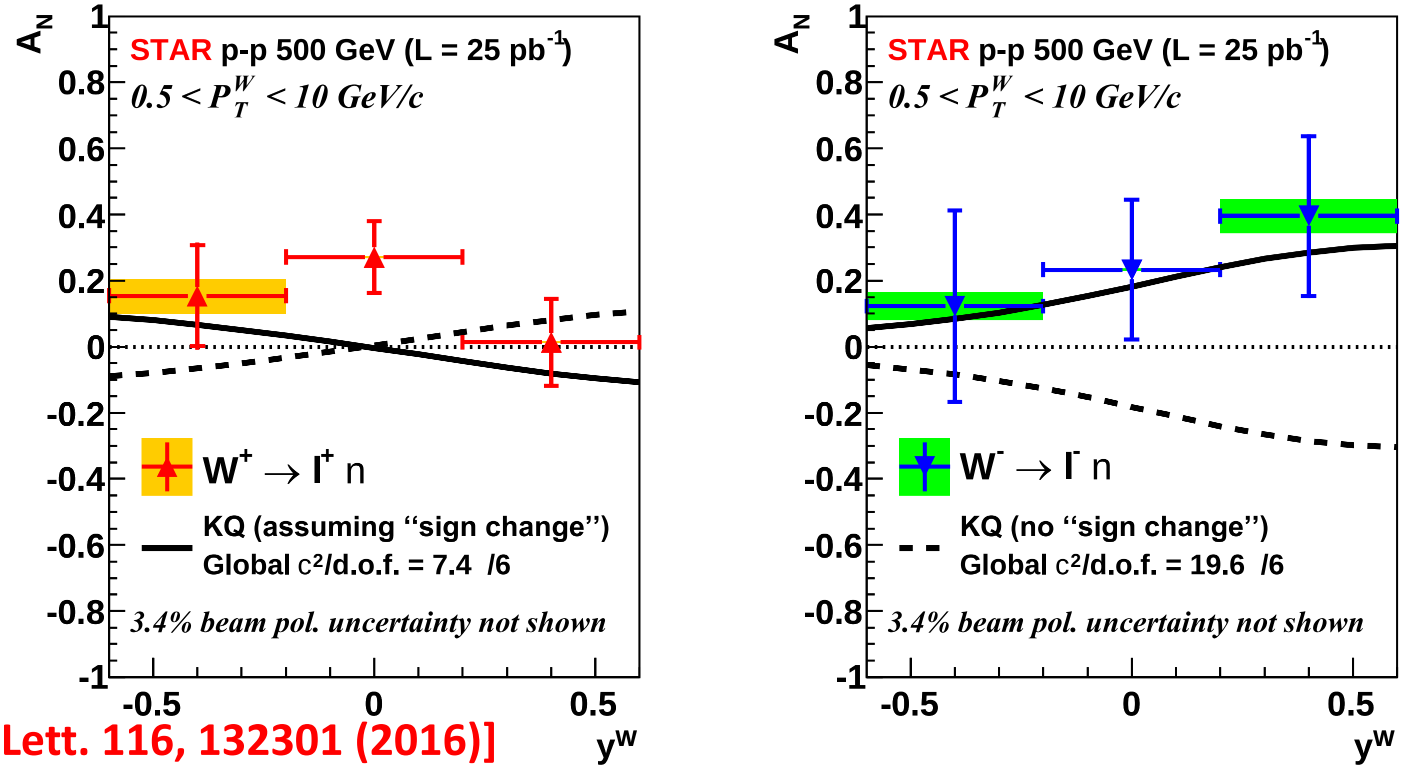
[Phys. Rev. Lett. 116, 132301 (2016)]



Results versus rapidity are compared with:

- **KQ model** [Z.-B. Kang and J. -W. Qiu, Phys. Rev. Lett. 103, 172001 (2009)]
  - It does not include TMD evolution
  - **Grey band** is the theory uncertainty
- **EIKV model** [M. G. Echevarria, A. Idilbi, Z.-B. Kang, I. Vitev, Phys. Rev. D89, 074013 (2014)]
  - Includes the largest prediction for TMD evolution
- **Grey hatched area** represents the current theoretical uncertainty on TMD evolution

The Sivers' sign change (no TMD evol.)



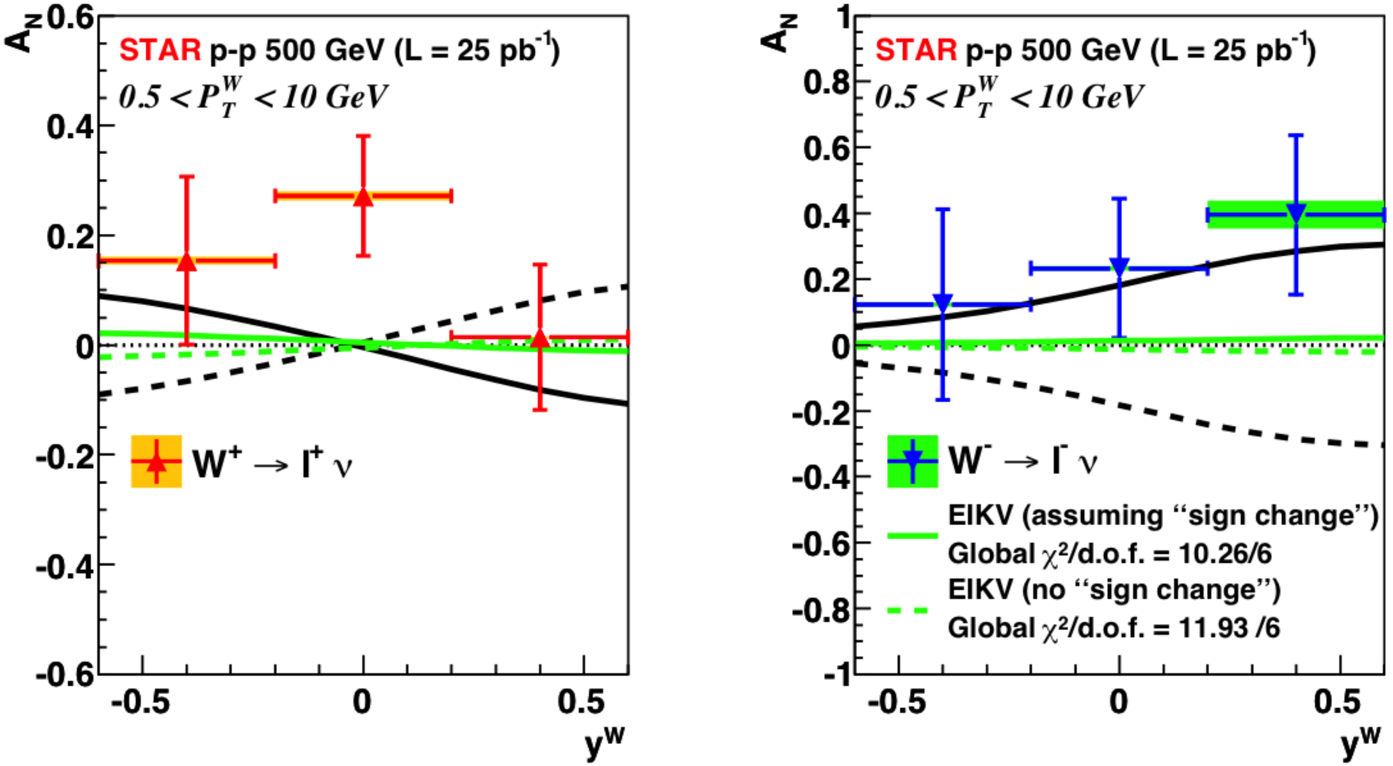
[Phys. Rev. Lett. 116, 132301 (2016)]

A global fit to the (unevolved) KQ prediction was performed:

- **solid line:** assumption of a sign change in the Sivers function → **Chi2/d.o.f. = 7.4/6**
- **dashed line:** assumption of no sign change in the Sivers function → **Chi2/d.o.f. = 19.6/6**

If there are no evolution effects,
our data favor the hypothesis of Sivers sign change

The Sivers' sign change (strong TMD evol.)



Size of the TMD evolution still uncertain

-> terms calculable from QCD + non-perturbative terms (need data)

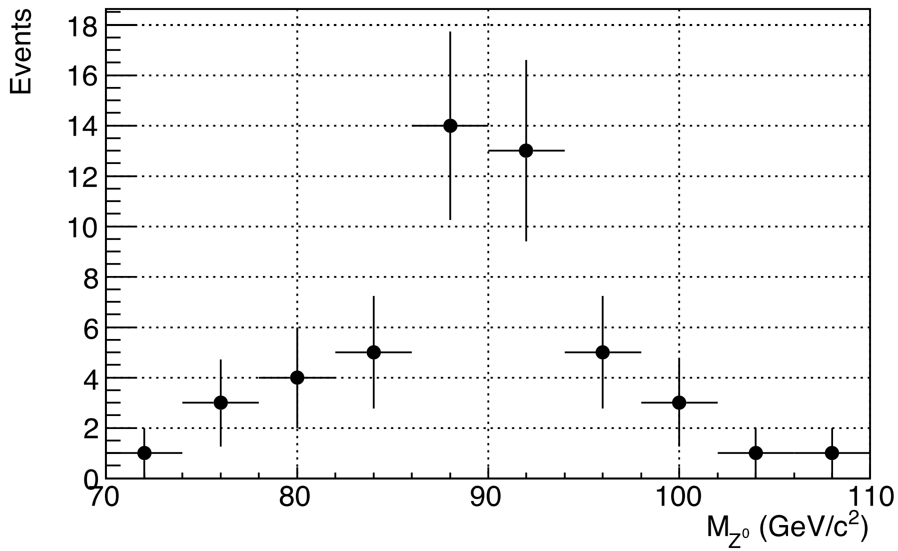
A global fit to the EIKV prediction (largest predicted evolution effect):

- **solid line:** assumption of a sign change in the Sivers function → **Chi2/d.o.f. = 10.26/6**
- **dashed line:** assumption of no sign change in the Sivers function → **Chi2/d.o.f. = 11.93/6**

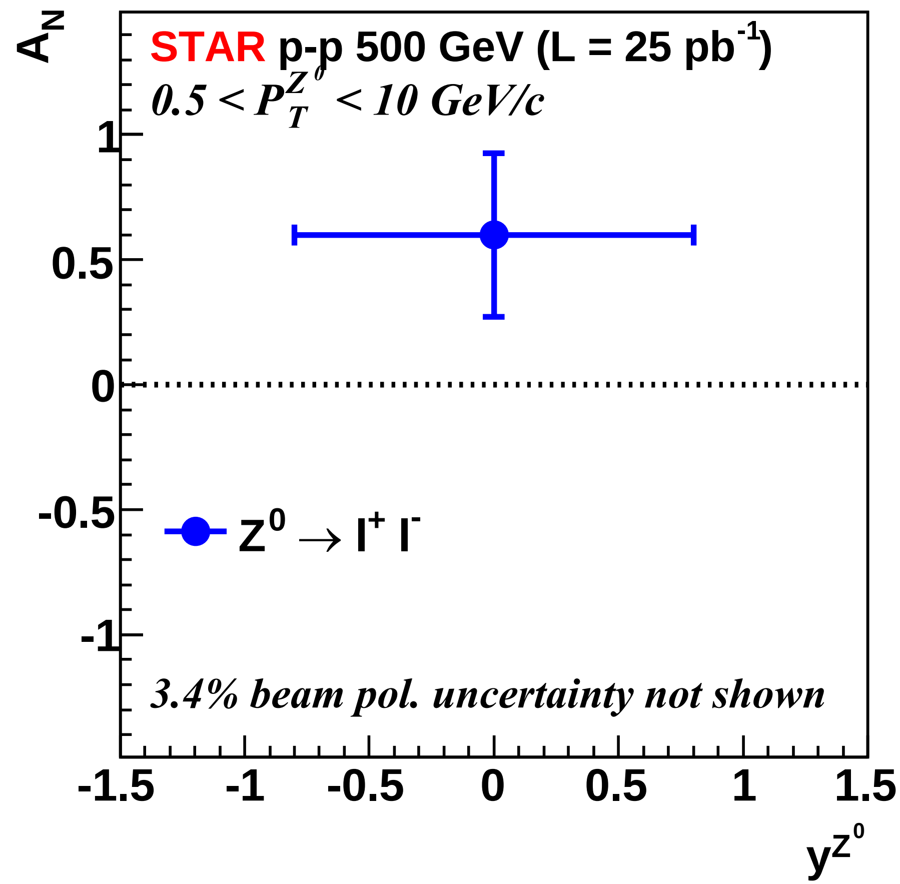
Our uncertainties are still too high to compare with predictions

Z^0 Asymmetry $pp \to Z^0 \to e^+e^-$

- **Clean experimental momentum reconstruction**
- **Negligible background**
- **electrons rapidity peaks within tracker accept. (|η|< 1)**

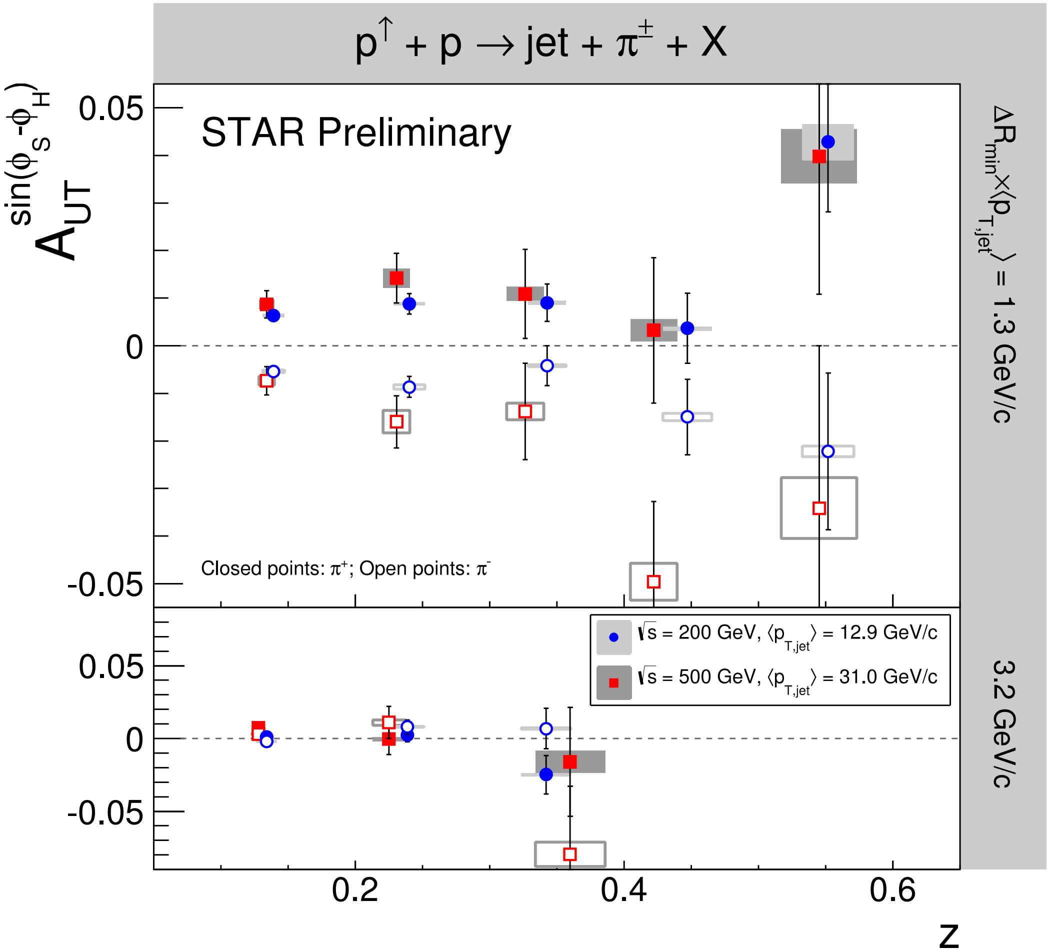


A_N measured in a single y, P_T bin



Final state mechanism: Transversity x Collins

$$A_{UT}^{p^{\pm}} \approx \frac{\boxed{h_1^{q_1}(x_1,k_T)} f_{q_2}(x_2,k_T)\hat{s}_{UT}(\hat{s},\hat{t},\hat{u}) \boxed{DD_{q_1}^{p^{\pm}}(z,j_T)}}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{s}_{UU} D_{q_1}^{p^{\pm}}(z,j_T)} \qquad z = \frac{p_t^h}{p_t^{jet}}$$



200 vs. 500 GeV Comparison:

- These measurements coupled with the interference fragmentation function (IFF) measurements at both 200 and 500 GeV are **sensitive to the evolution and universality of TMD functions.**
- These results could be sensible to the size of potential factorization-breaking in Collins in p+p.
- dependence of the Collins FF on pion transverse momentum (j_T)

What we see

Non-zero Collins asymmetry

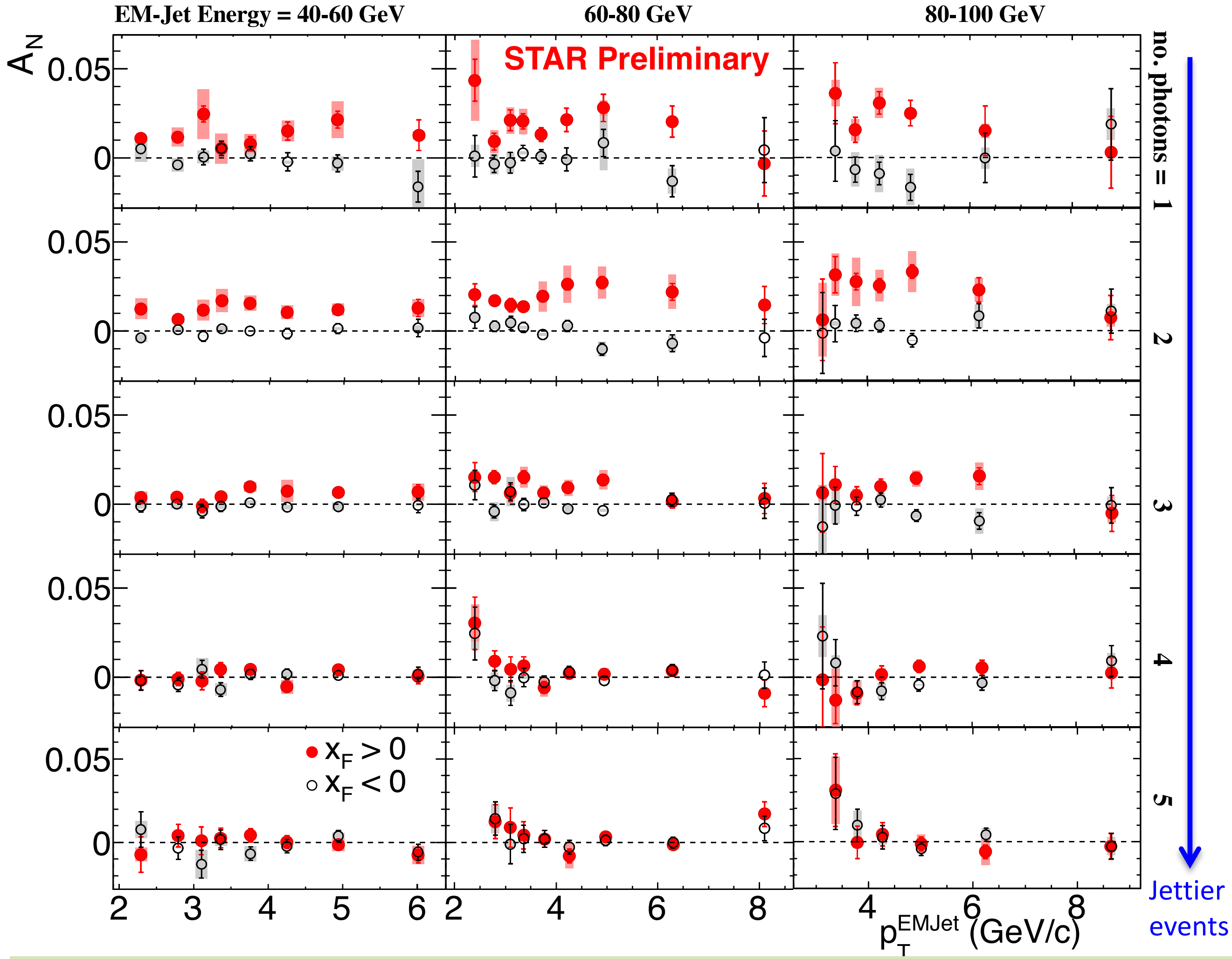
-> Access to transversity!

Similar size asymm. in 200 and 500 GeV

-> Small TMD evolution?

-> Cancellation in num/denom may also be the key

New surprise in Spin physics: a diffractive effect?

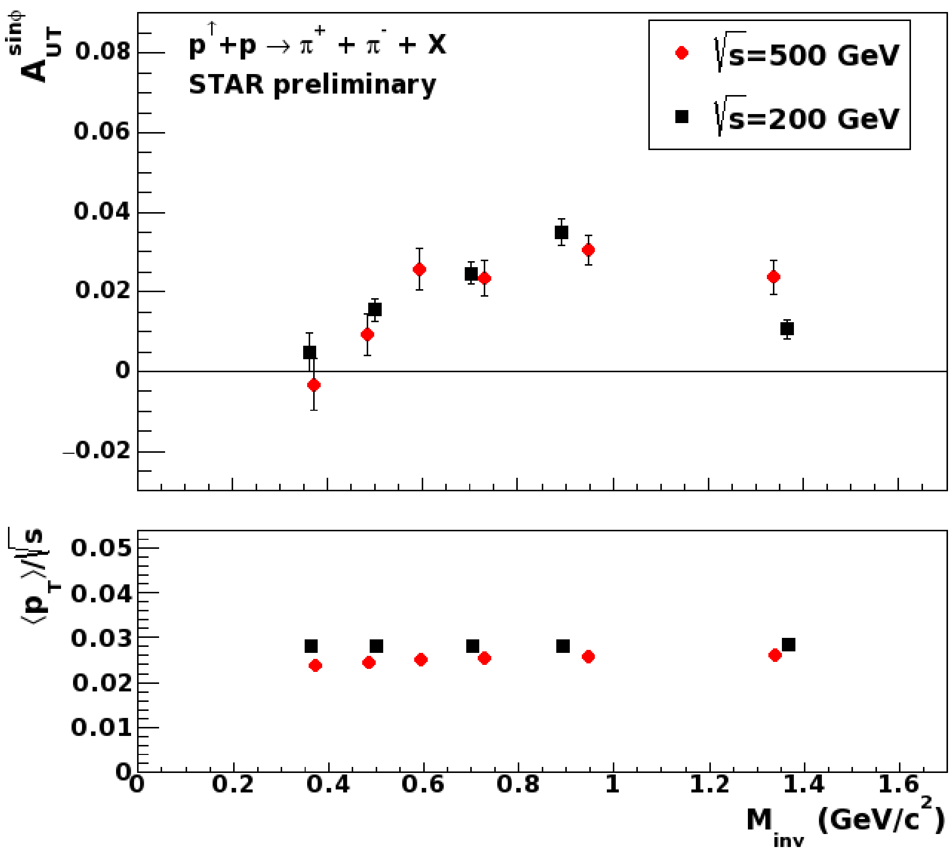


A_N for different # photons in EM-Jets

- 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- A_N decreases as the event complexity increases (i.e.,the "jettiness")
- Several other Asym. for jettier events are also very small. Collins contribution is ~1% over the entire x_F range

- Sivers-type asymmetry in the jets is too small to explain π^0 asymmetry
- A_N for π^0 may be dominated by hard diffraction: $p^{\uparrow}+p \rightarrow \pi^0 + p' + X$
- Run 15 – STAR has collected data using RPs to measure forward scattered protons

Transversity x Di-hadron IFF



[Bacchetta and Radici, PRD 70, 094032 (2004)]

$$A_{UT}^{\sin(\varphi_{RS})} \propto h_1 \otimes H_1^{\sphericalangle}$$

φ_{RS} -> azimuthal angle between the proton spin and the di-hadron plane

- **Much improved statistical uncertainties!**
- **Again... similar size asymmtry in 200 and 500 GeV**

What we see

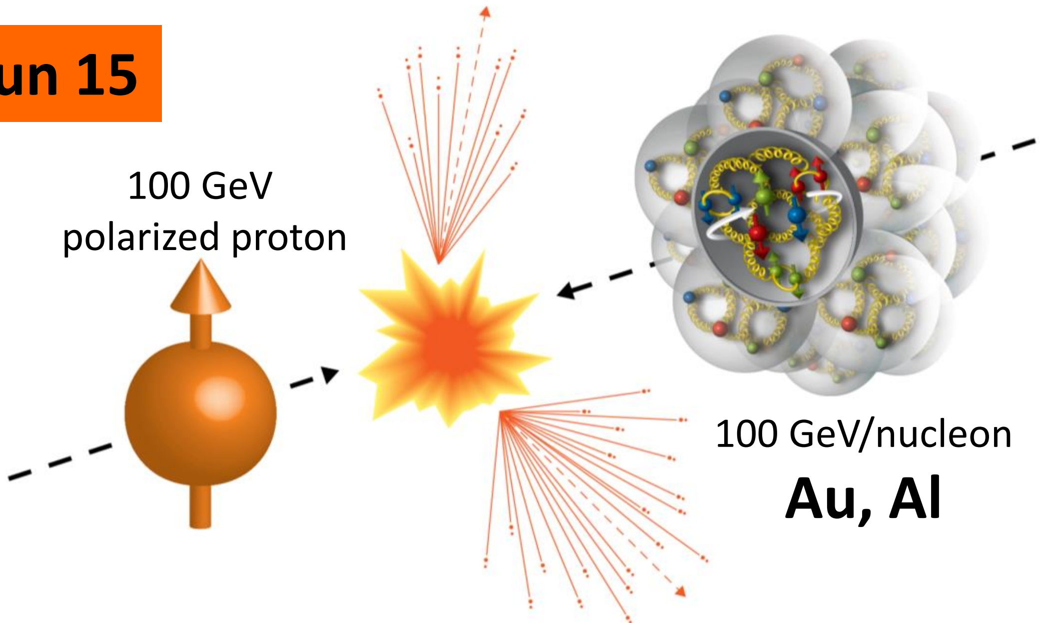
Non-zero IFF (Interference Fragmentation fcn.) asymmetry in pp

-> A complementary way to access to transversity!

Signal enhancement around the ρ-mass region in both 200 and 500 GeV

First polarized pA collisions @ RHIC

RHIC Run 15



RHIC's unique opportunities:

→ polarized p↑(d,He) A (Au, C, Cu, …)

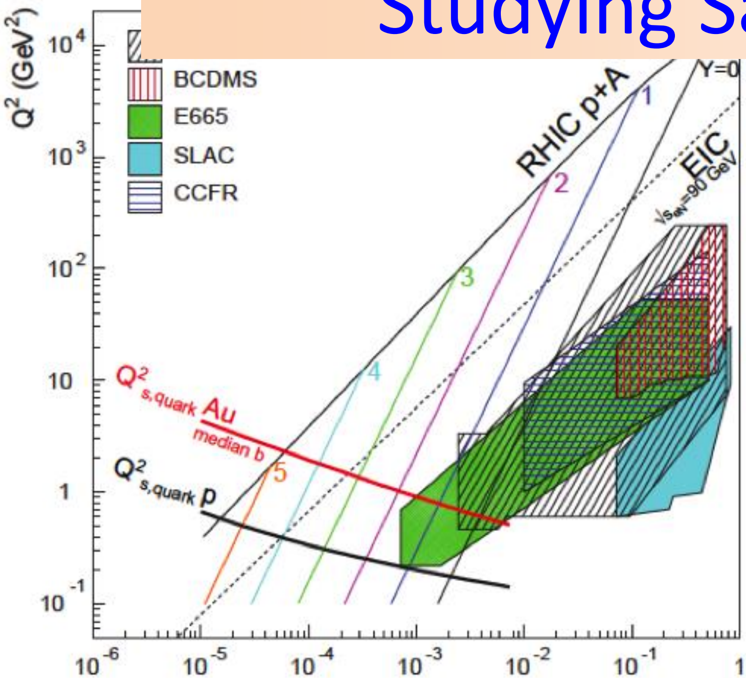
→ A-scan unique to RHIC

→ Energy scan to separate different underlying mechanisms

Things to investigate:

- **Theory prediction based on QGP ->** A_N decreases with increasing size of the nuclear target
- **pQCD factorization based approach ->** A_N remains the ~same for all nuclear targets

Studying Saturation Through Spin



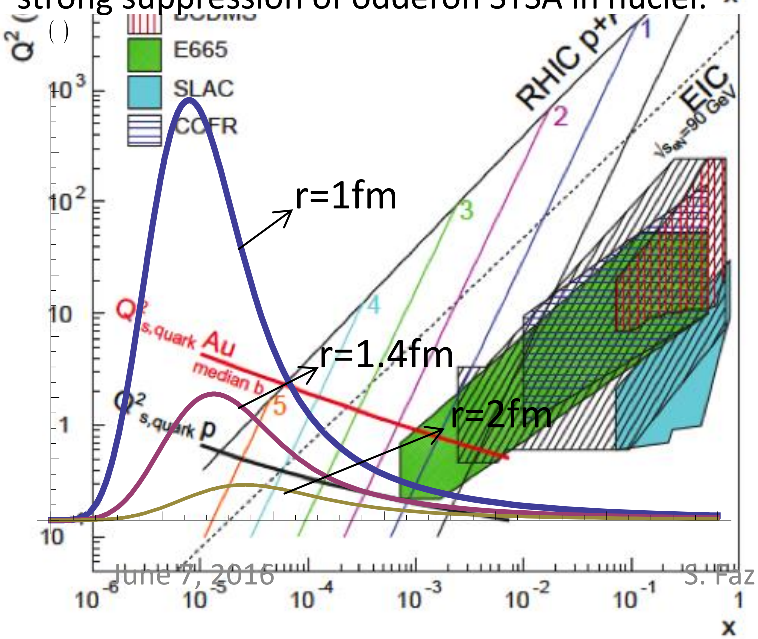
- Very unique RHIC possibility p↑A
- Gluon saturation signature in transverse single spin asymmetries A_N
- Suppression is enhanced in nuclei

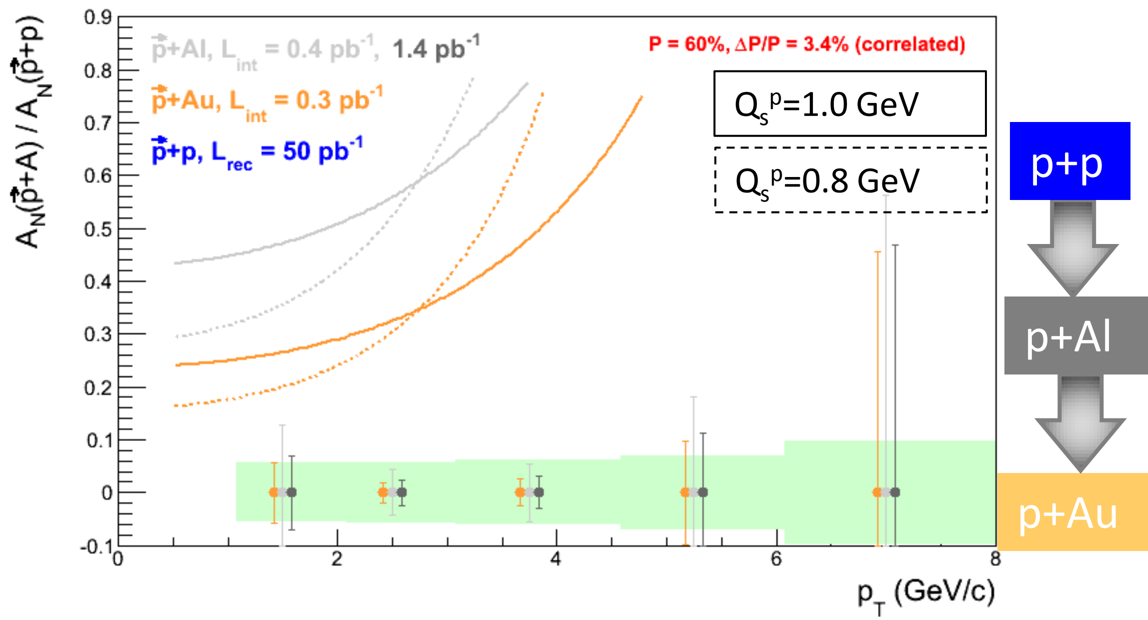
$$Q_s^A = A^{1/3} Q_s^p$$

- Suppression of A_N in p↑A provides sensitivity to Q_s

arXiv:1106.1375 & arXiv:1201.5890

strong suppression of odderon STSA in nuclei.

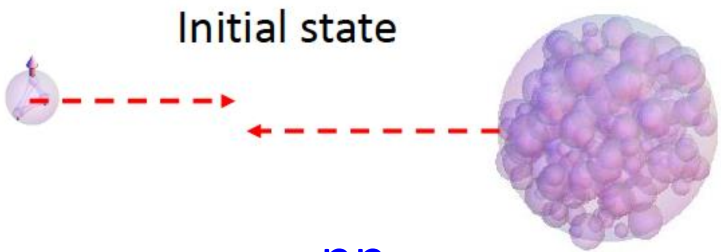


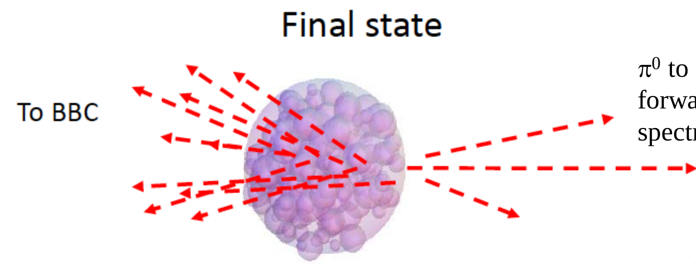


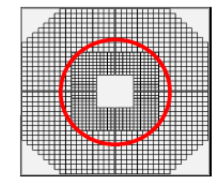
First results from p↑A @ STAR

STAR Run-15:

A_N data for p↑p, p↑Au and p↑Al at $2.8 < \eta < 4.0$



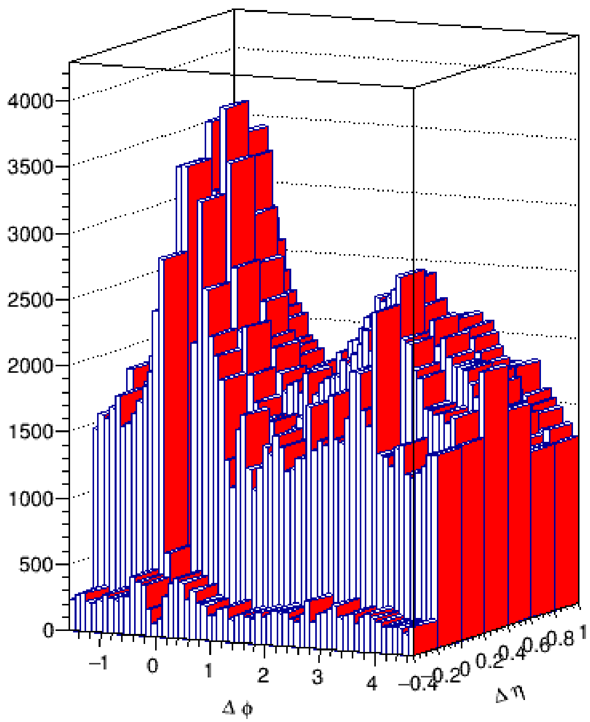




pp

2 cluster distribution

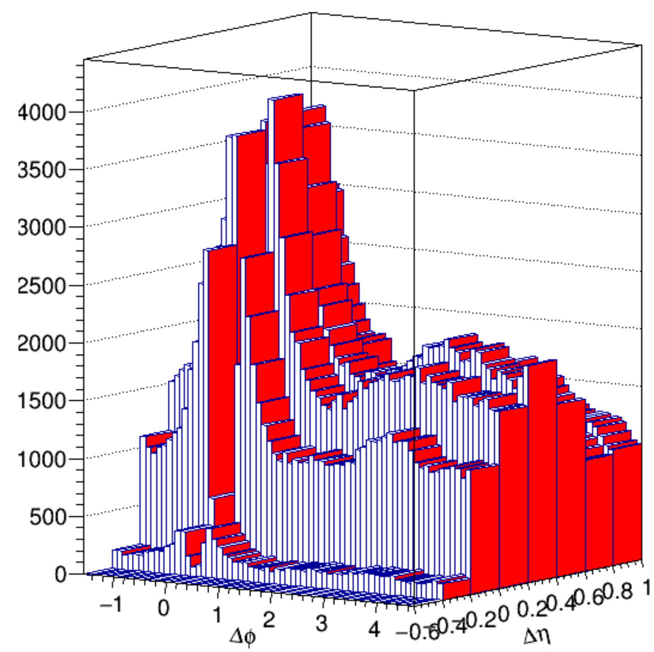
pAu



π^0:

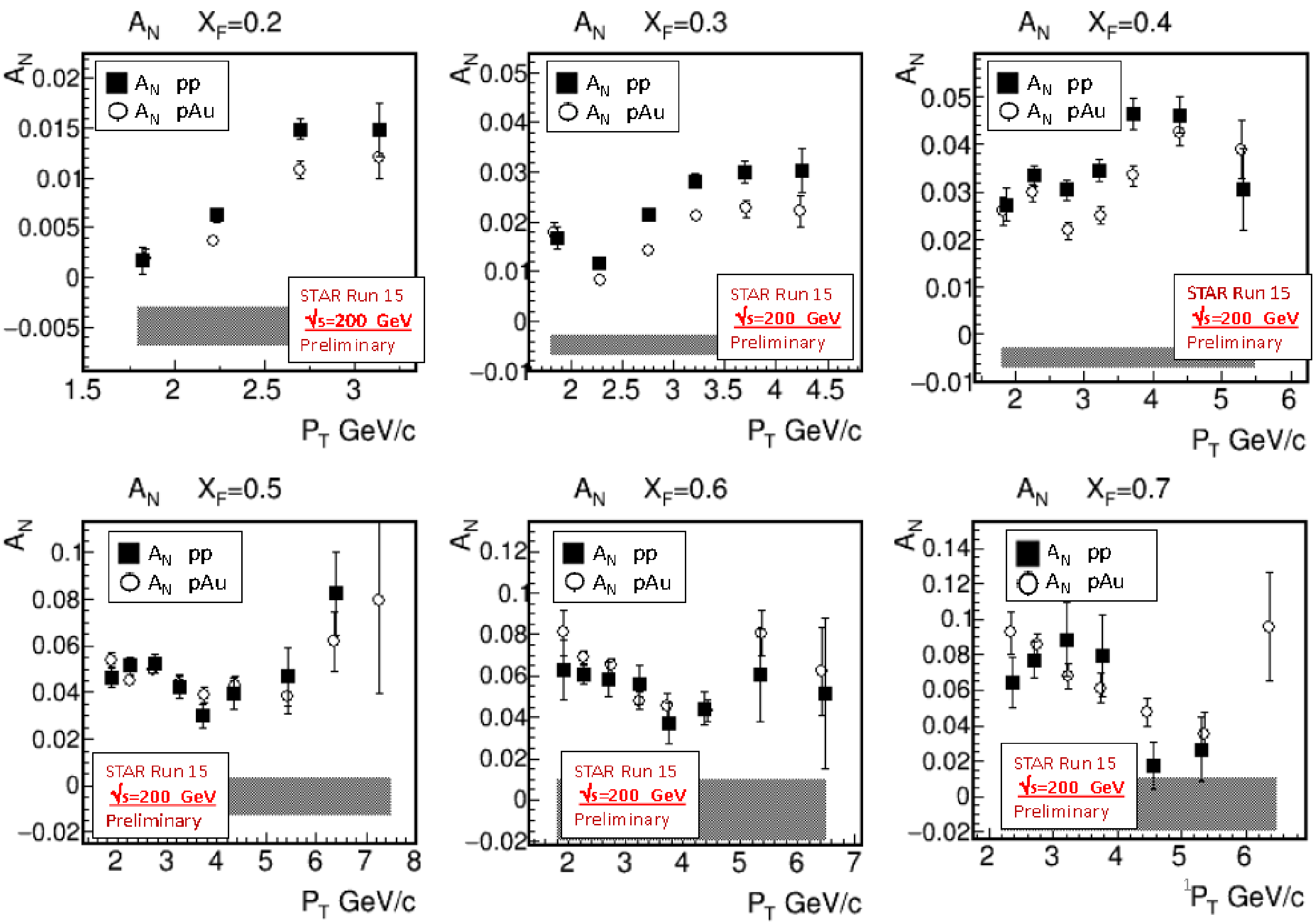
$0.25 < x_F(\pi^0) < 0.35$

$3.55 < p_T(\pi^0) < 4.05$ GeV



TSSA in d+Au

STAR: π^0 A_N in pp and pAu at √s=200 GeV



Luminosity:

pAu= 204.6 nb^{-1}

pp= 34.8 pb^{-1}

<polarization>

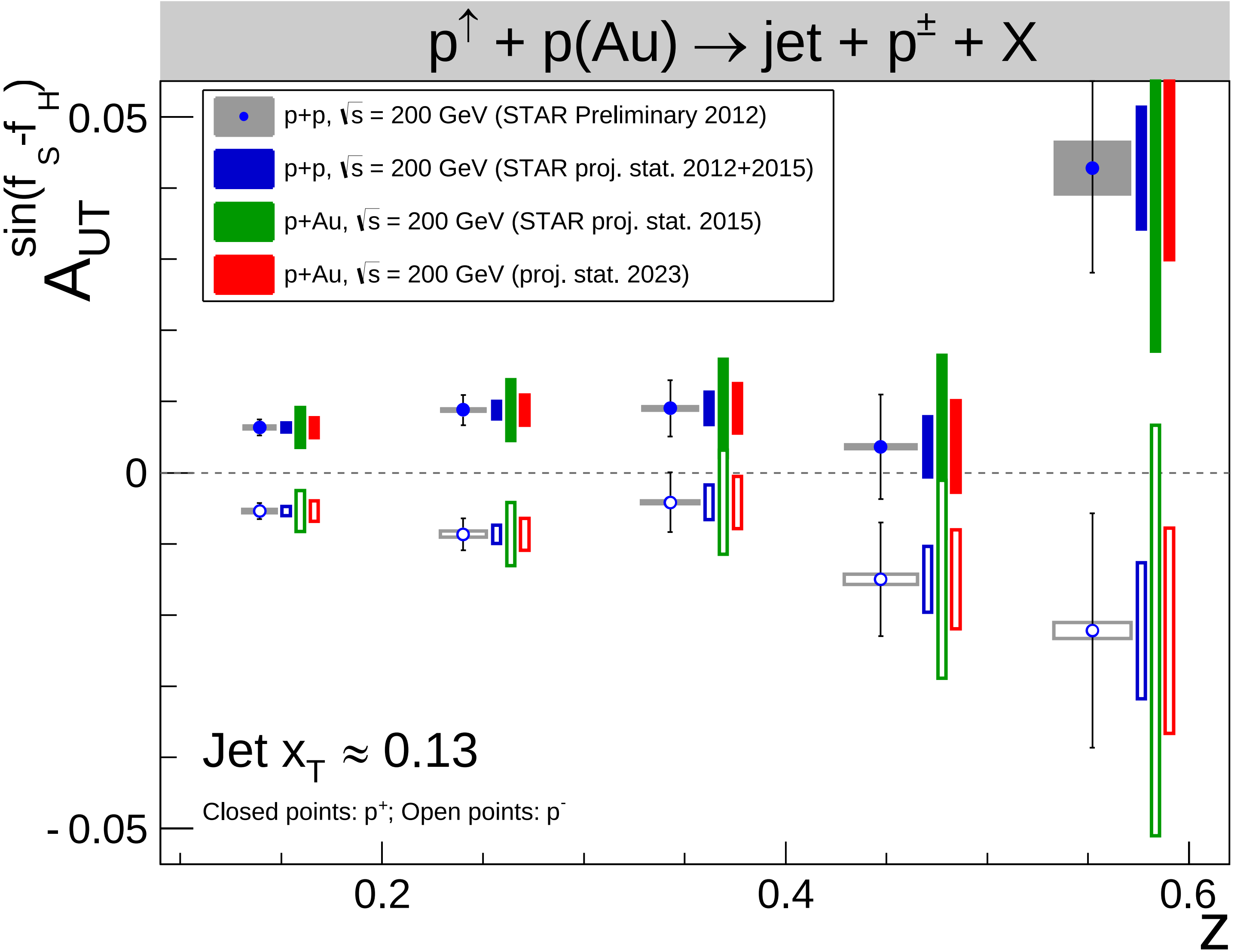
pAu= 60.4 ± 2%

pp= 55.6 ± 2%

Shaded bands show the systematic uncertainty, dominated by the dependence of A_N on the BBC multiplicity → central vs. peripheral collisions

Only minimal suppression effect observed for A_N in pAu

Nuclear modification of TMDs



Collins FF in p+Au

Analysis of run 15 data ongoing...

First study of a nuclear modification of a spin observable, ever!

… and the future?

Sivers future program at STAR?

Present results, obtained with a pilot sample of 25 pb^{-1} show a proof-of principle

Full kinematic reconstruction of weak bosons is possible at STAR

Main physics goals:

- How strong is the TMD evolution?
- What is the contribution to the Sivers function from sea-quarks?
- Conclusive test of the Sivers' sign change
- Precise measurements suitable for 3D imaging of protons in momentum space

How?

→ **Measure A_N for direct-γ, $W^{\pm}$, Z^0, DY**
→ **DY and $W^{\pm}$, Z^0 give Q^2 evolution**
→ **$W^{\pm}$ give sea-quark Sivers**
→ **All four processes give sign change**

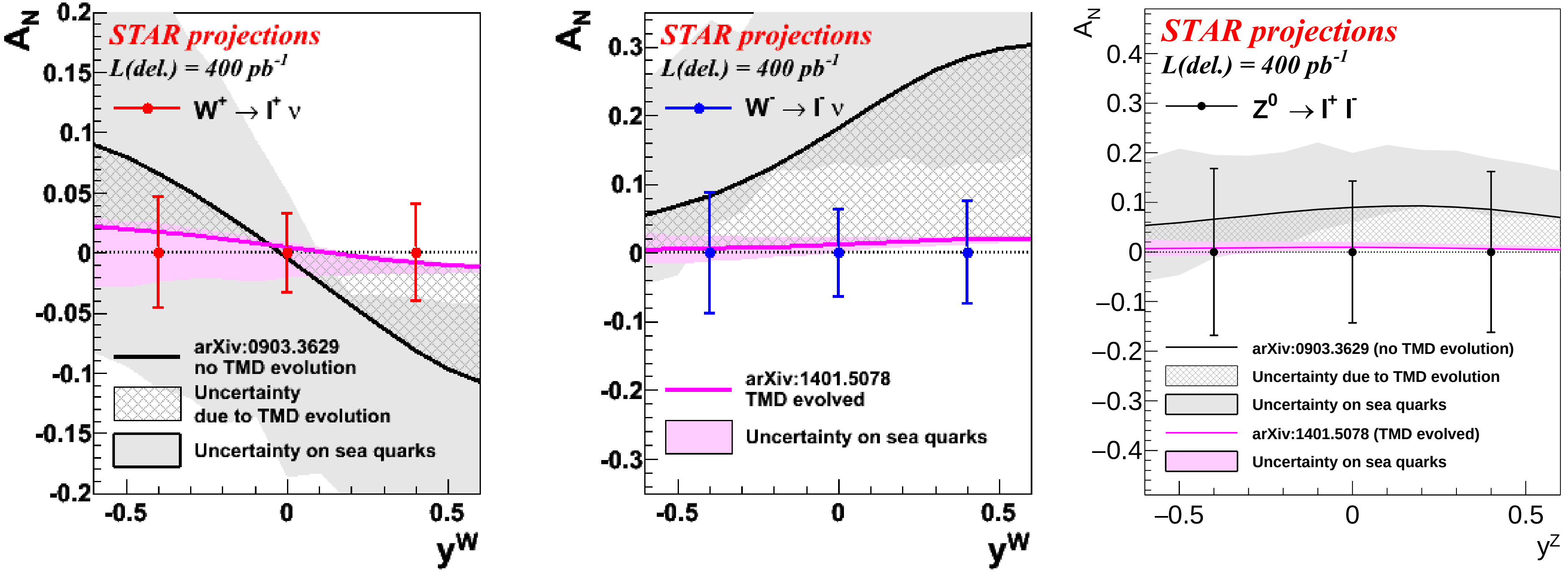
All we need is more data!

Run 17 - Assumptions:

integrated delivered luminosity of 400 pb^{-1}

→ **13 weeks** transversely polarized p+p at 510 GeV
→ electron lenses are operational and dynamic β-squeeze is used throughout the fill
  → smoothed lumi-decay during fills
  → reduced pileup effects in TPC → high W reconstruction efficiency

The future: A_N of Weak bosons at STAR

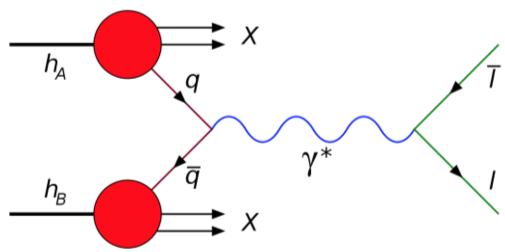


Large statistics will allow us to

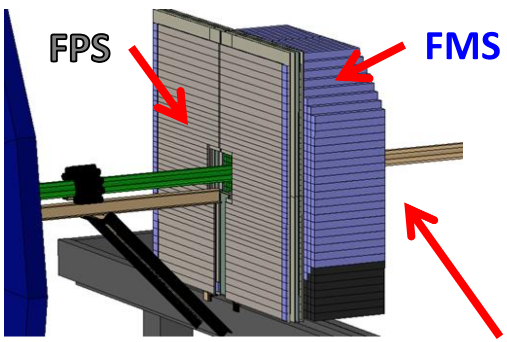
- **Precisely measure A_N for Ws within a few %** in several P_T, y bins.
- Measure the very clean **Z^0 channel**.
- Test sign change if evolution is less than factor ~5

RHIC plans to deliver ~400 pb^{-1} transverse p-p in 2017

The future: A_N of Drell-Yan at STAR



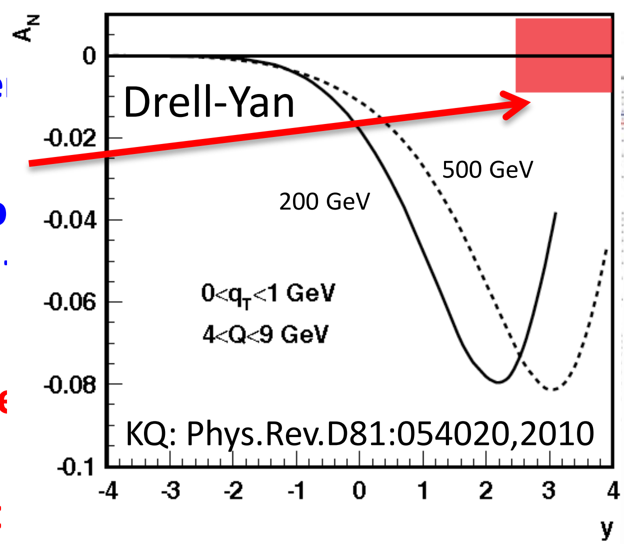
- **Very Challenging: (RHIC QCD WP arXiv:1602.03922)**
  - QCD background ~10^5-10^6 larger than DY cross-section
  - Probability of wrongly identifying a decay electron to be suppressed to ~0.01% while maintaining efficiency in identifying electrons
- **COMPASS (CERN) and proposed E-906/SeaQuest (FNAL)** pursue the investigation of TMD through this process
- **STAR can measure it...** after an upgrade
  - A forward Post-Shower detector will be installed behind the the FMS detector and its Pre-Shower

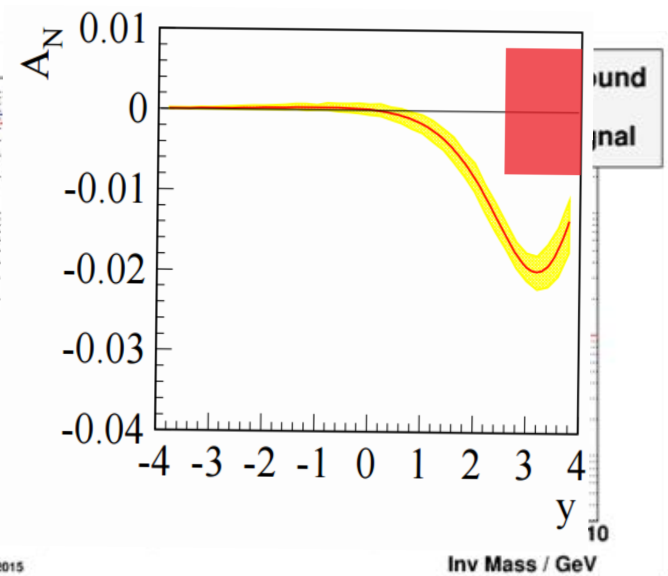


post-showe

STAR projected uncertainty

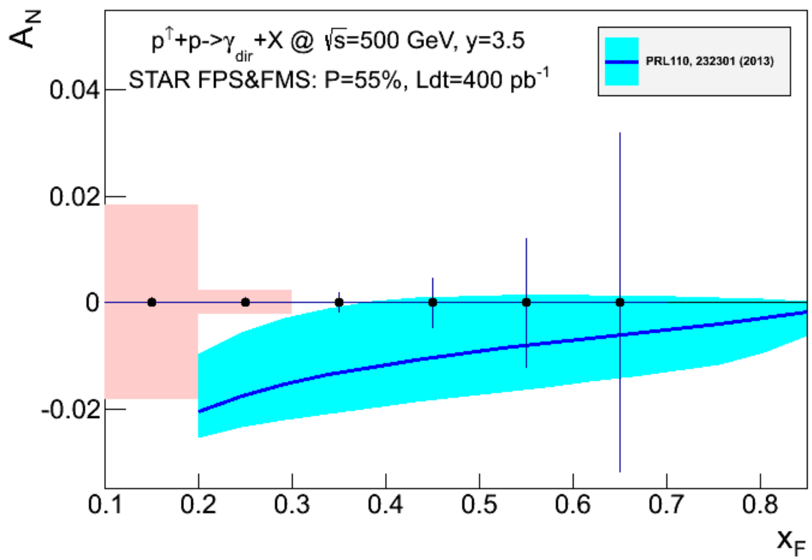
The expected yields o
background after





The proposed forward-dete
post-shower) provides the
to allow our measurement

The future: A_N of direct-photons at STAR



A_N for direct photon production:

- ❑ sensitive to sign change, but in TWIST-3 formalism
- ❑ not sensitive to TMD evolution
- ❑ no sensitivity to sea-quarks; mainly u_v and d_v at high x
- ❑ collinear objects but more complicated evolutions than simple DGLAP
- ❑ indirect constraints on Sivers fct.

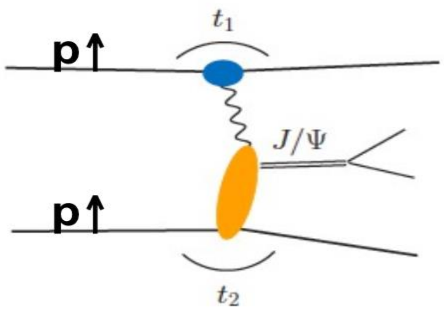
How do we access the sign change?

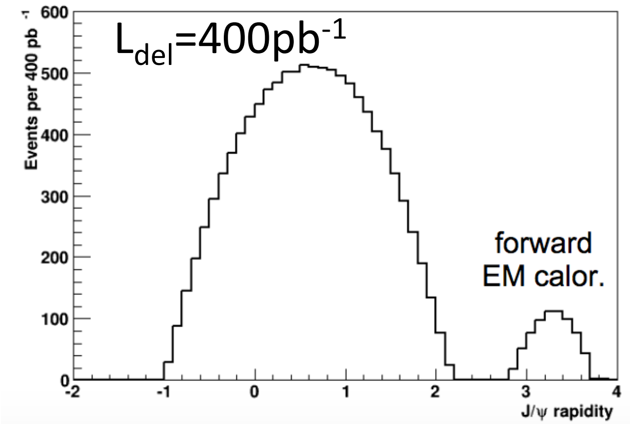
If the correlation due to different color interactions for initial and final state between the **Sivers fcn** and the **twist-3 correlation fcn** in the k_T integral would be violated, the asymmetry would be positive but the same magnitude

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

Not a replacement for a $A_N(W^{+/-}, Z^0, DY)$ measurement but an important complementary piece in the puzzle

The future: j/ψ in $p^{\uparrow}+p^{\uparrow}$ UPC





Trigger on:

- 2 EM showers in STAR calorimeters (j/ψ → e^+e^-)
- hit in either Roman Pots (RPs)
- no BBC activity (ensure its a diffractive event)

RPs acceptance:

- **0.19 < |t| < 1.9 GeV²**
- detects either/both protons from:
  - source of photon (lower |t|)
  - target of photons (higher |t|)

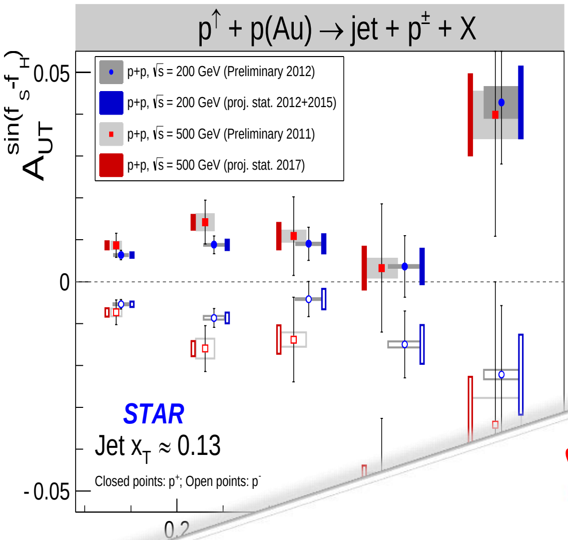
Projected statistics: **~11k** events in run 17

- **Run 17:** large $p^{\uparrow}+p^{\uparrow}$ sample to be collected, L_{del}=400pb^{-1}
- **through transverse asymmetry A_{UT}** -> Access to **GPD Eg** -> proportional to the gluon orbital angular momentum **Lg**
  - **$A_{UT} \neq 0$ → Eg ≠ 0 → Lg ≠ 0**
- **This is the only way to look at the GPD Eg before the construction of an EIC (unique at RHIC!)**

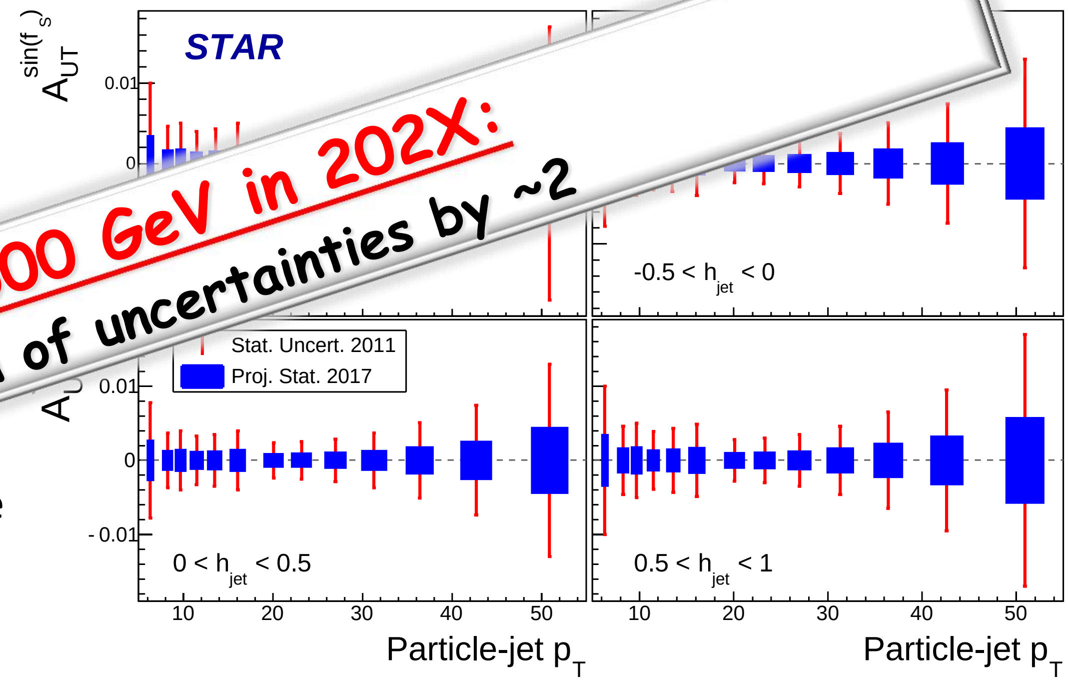
The longer term future: mid-rapidity observables

Transversity x Collins

@ 200 GeV in 2015&2023 and 500 GeV in 2017 / 202X:



Sivers function through TWIST-3



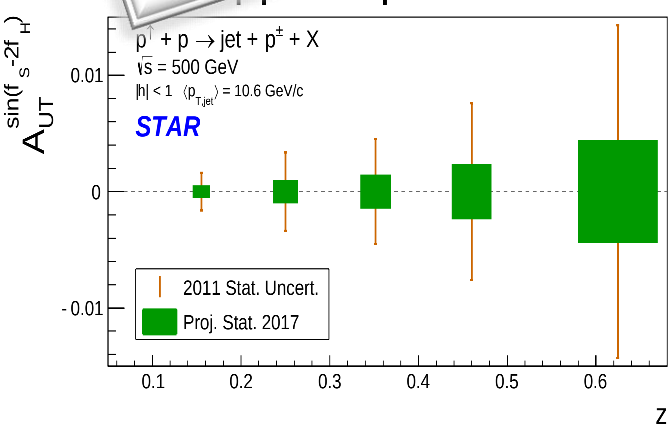
line...

→ c... ...ation for the ridge

se... pp and pA

more 500 GeV in 202X:

reduction of uncertainties by ~2



To have high precision data at different $\sqrt{s}$

→ constrain TMD evolution

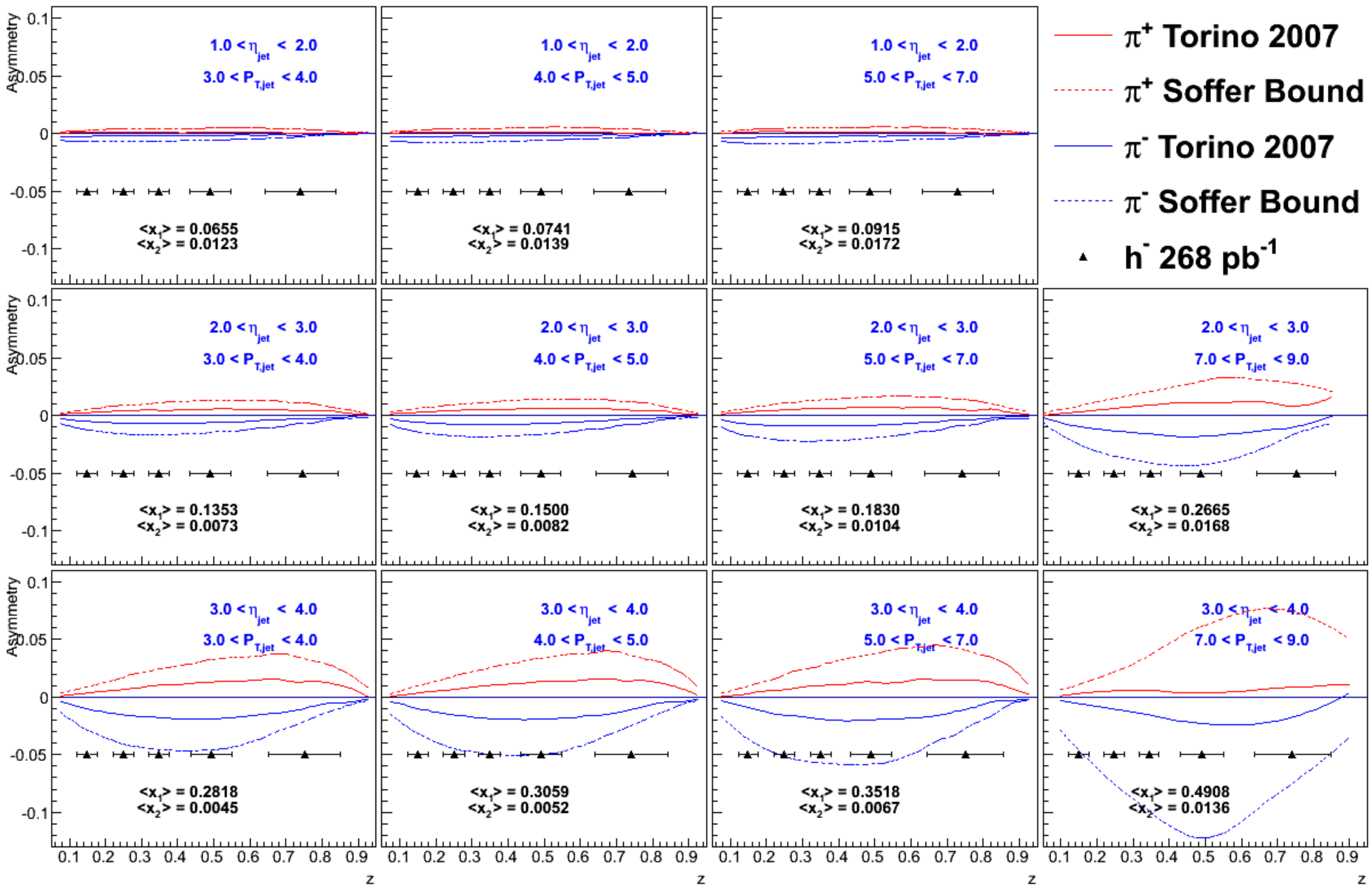
→ fixed x and Q^2 → p_T different

The longer term future: forward-rapidities

@ 200 GeV in 2023 and 500 GeV in 202X → 2021:

→ 500 GeV: access high x and jets at forward rapidities

Transversity x Collins FF



At 200 GeV: A_N for charged hadrons → rigid test on Twist-3 FF

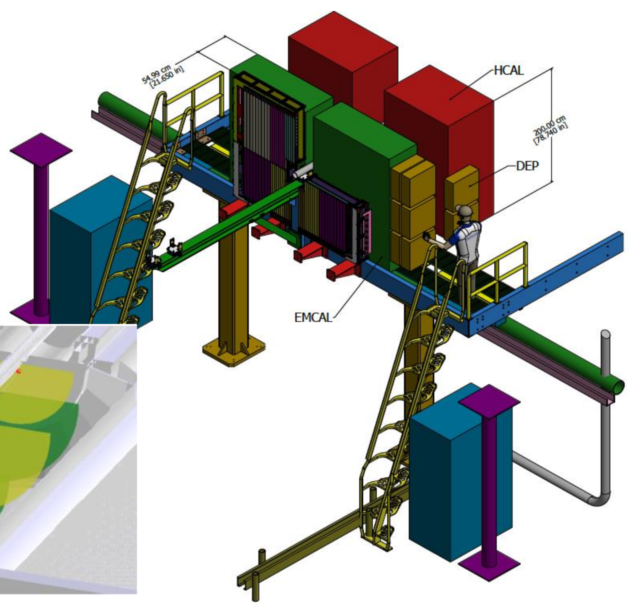
The longer term future: STAR forward upgrade plans

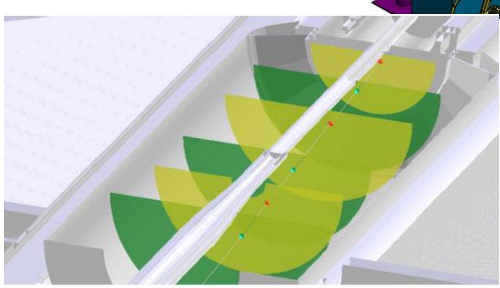
- **What is needed (Hardware):**
  - **wide acceptance mid-rapidity detector with good PID**
  - **forward rapidities ($1 < \eta < 4.5$) Ecal + HCal + charge identification**

  For details see:

  → **RHIC Cold QCD Plan**

  → **https://drupal.star.bnl.gov/STAR/system/files/FCS_FTS-proposal_20160119_final_0.pdf**





Ecal:
reuse PHENIX Ecal (PbSc)
$\sigma_E/E \sim 8\%/\sqrt{E}$

Hcal (PbSc):
design a la STAR fHCal and EIC fHCal
$\sigma_E/E \sim 70\%/\sqrt{E}$

Tracking (Si):
4-6 strip-disks

Add to existing STAR at rapidity
$2.5 < \eta < 4.5$

Conclusions

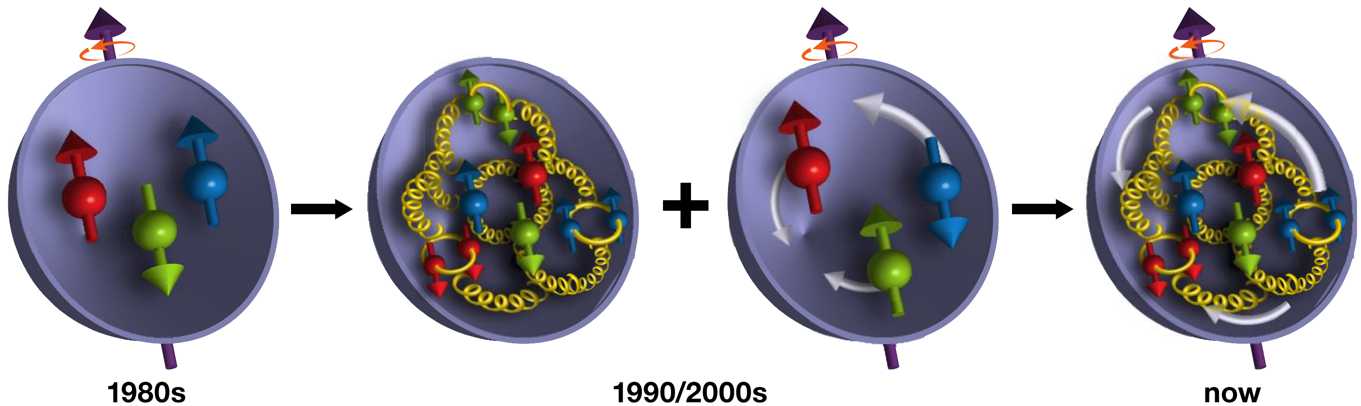
- **RHIC is the world's only polarized collider -> unique opportunities**
- **STAR has recently released exciting results in transverse-spin physics**
  - **World's first experimental test of the non-universality of the Sivers function through measuring A_N of fully reconstructed $W^{\pm}$ and Z^0 bosons**
  - **Understanding the final state mechanism using jets and di-hadron IFF -> two ways to access quark transversity**
  - **first investigation of nuclear TMDs and saturation effects in $p^{\uparrow}$+A**
- **RHIC run 17 data (up to L~400 pb^{-1}) can give statistical significance to:**
  - **Pin down TMD evolution**
  - **Investigate the contribution from sea-quarks to the Sivers fcn.**
  - **Ultimate test of the Sivers' sign change if the size of the evolution effect is less than a factor 5, STAR is the only experiment that can measure A_N for γ, $W^{\pm}$, Z^0, DY, all in one venue, simultaneously!**
  - **Study the GPD Eg through measuring A_N of j/ψ in p+p: the only opportunity before the realization of an Electron-Ion Collider**
  - **Longer term goals for further investigation of Saturation, Collins, transversity**

Summary of the program

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linear pol Gluons, Gluon Sivers in Twist-3 First look on GPD Eg	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR None None
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for diffractive events	Yes Forward instrum. None
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. None Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. None Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity	Yes Forward instrum. None
	202X	$\vec{p}\vec{p}$ @ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

BACKUP

The structure of a proton

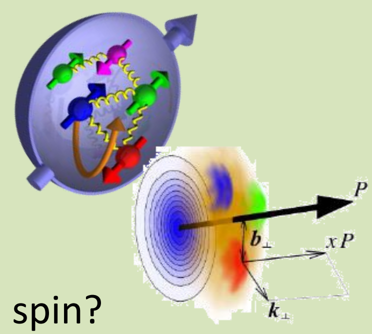


Today we know that a proton (nucleon) is a very complex object!

What is the dynamic structure of the nucleons?

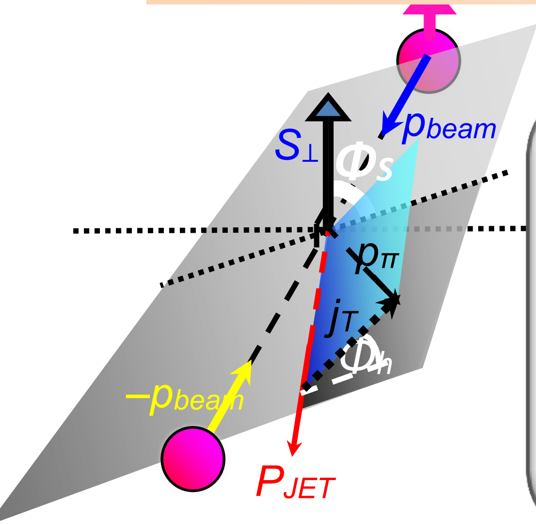
Nucleon imaging: How are sea quarks and gluons and their spin distributed in space and momentum inside the nucleon?

2D+1 picture in momentum and coordinate space



- How are these quark and gluon distributions correlated with the over all nucleon properties, such as spin direction?
- What is the role of the motion of sea quarks and gluons in building the nucleon spin?
- **Visualize color interactions in QCD**
  understand deep aspects of gauge theories revealed by k_T dependent distributions

Transverse momentum dependent PDFs &FFs

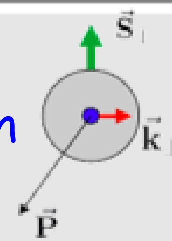


observable: azimuthal modulations

of 6-fold differential SIDIS cross section $\frac{d\sigma}{dx\,dQ^2\,dz\,d\phi_s\,d\phi_h\,dp_T^h}$

example:

Sivers function



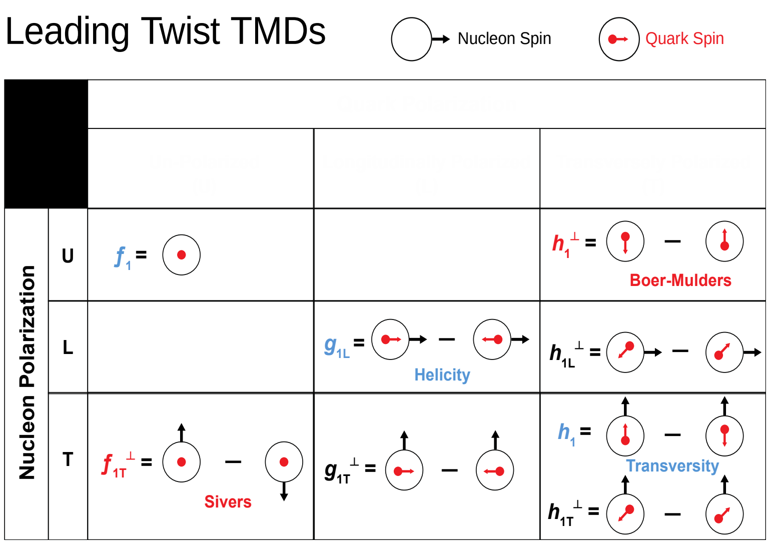
correlation of nucleon's transverse spin with the k_T of an unpolarized quark

→ $\sin(\phi_h - \phi_s)$ modulation

$$f_{q/P^\uparrow}(x,\mathbf{k}_\perp,S) = f_1(x,\mathbf{k}_\perp^2) - \frac{\mathbf{S}\cdot(\hat{\mathbf{P}}\times\mathbf{k}_\perp)}{M} f_{1T}^\perp(x,\mathbf{k}_\perp^2)$$

unpolarised TMD 

Sivers function 



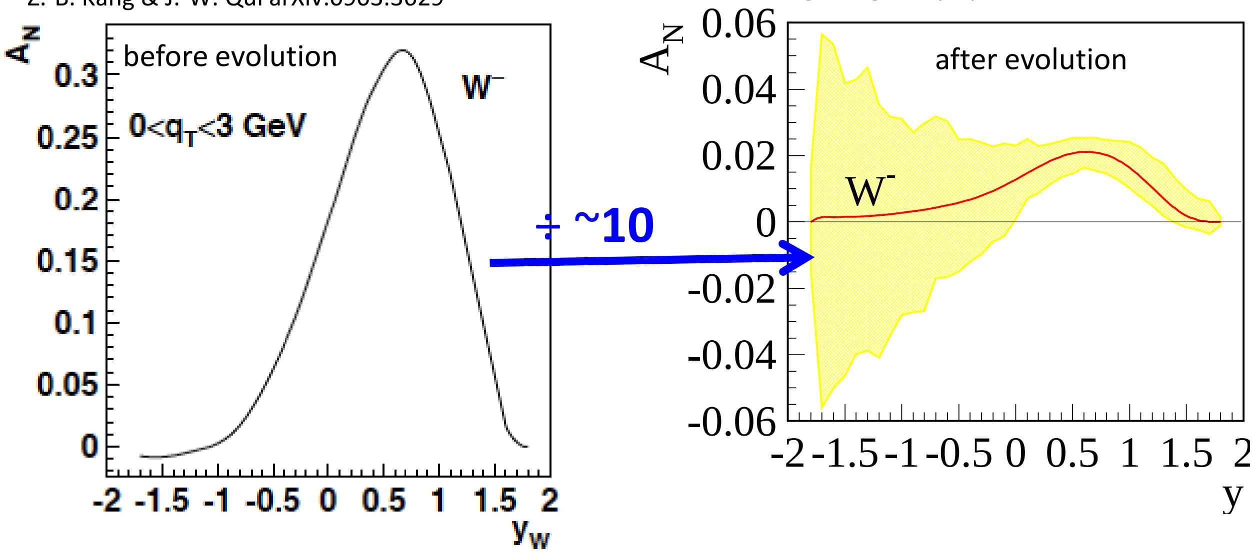
Leading Twist TMD FF

N \ q	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$H_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

Motivations – The TMD evolution

Z.-B. Kang & J.-W. Qui arXiv:0903.3629

Z. Kang: original paper arXiv:1401.5078



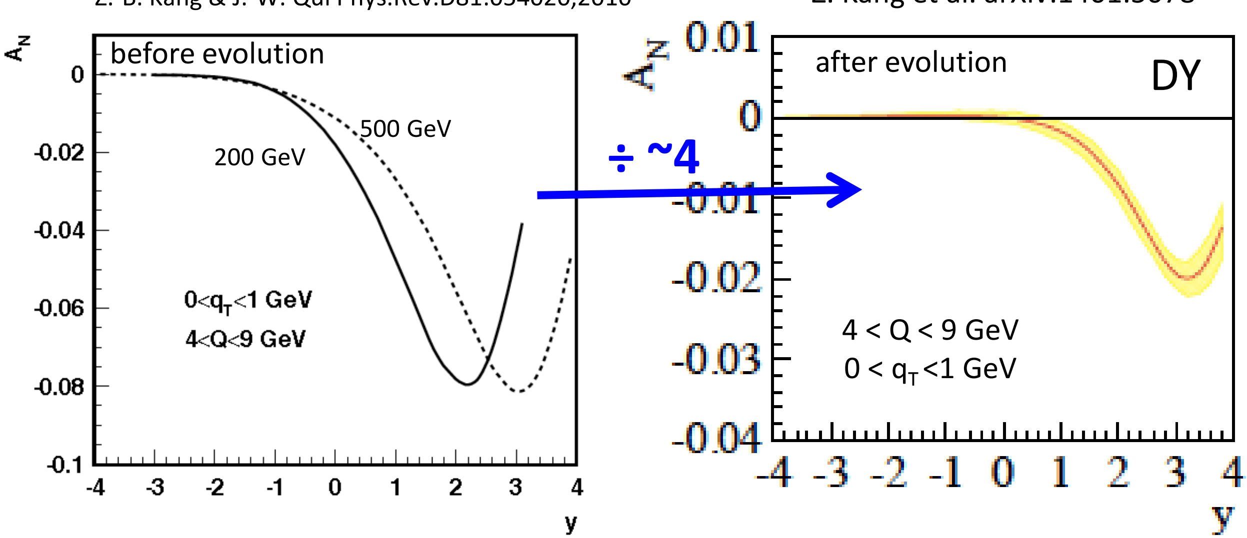
Very strong evolution effects

size of the effect still under discussion in theory community

For details see
Talk by J. Collins in this session
and
J. Collins, T. Rogers, Phys.Rev. D91 (2015) 7, 074020

Z.-B. Kang & J.-W. Qui Phys.Rev.D81:054020,2010

Z. Kang et al. arXiv:1401.5078



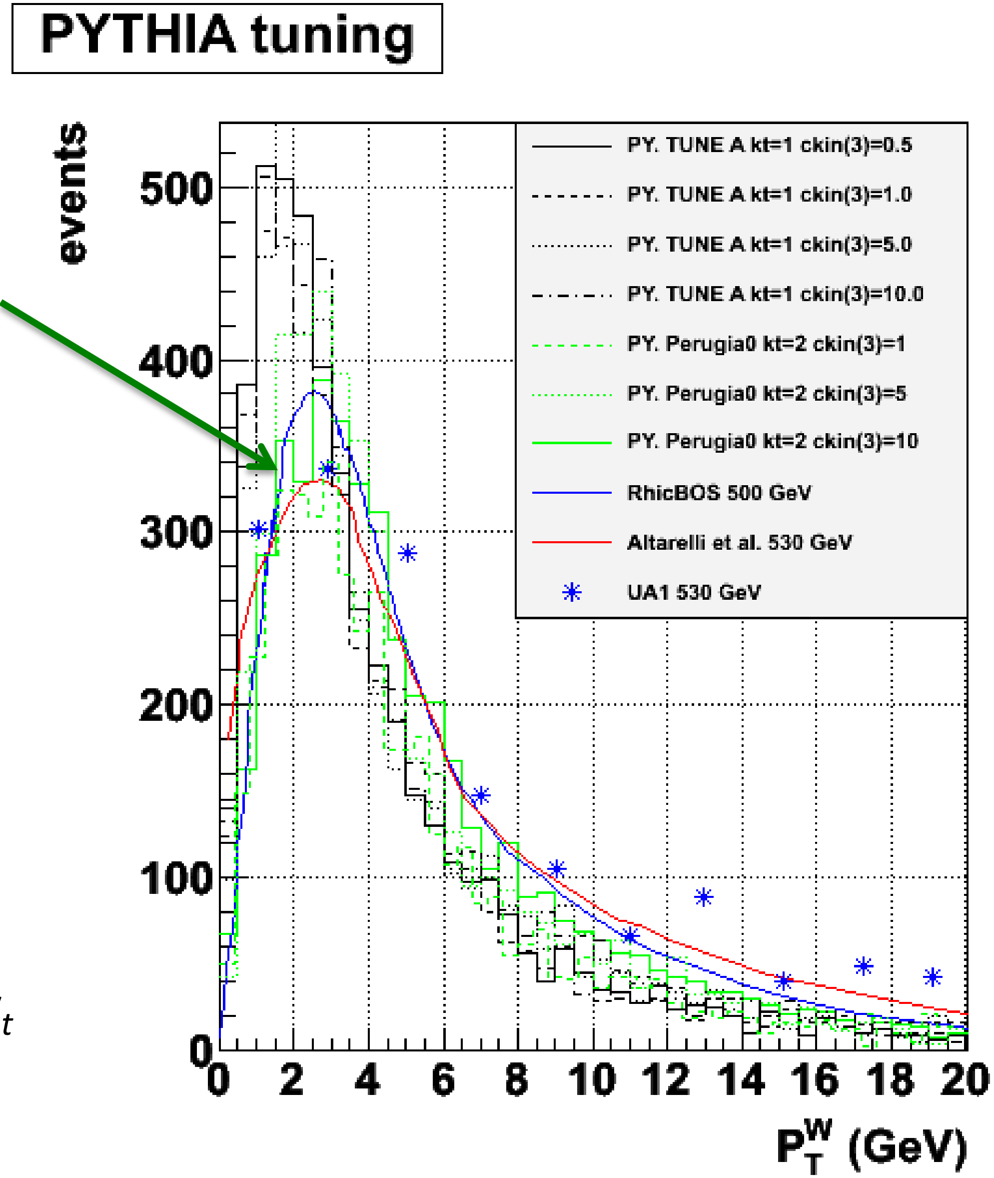
Data & MC

Monte Carlo

→ **PYTHIA** reconstructed through GEANT simulated STAR detector

→ **Perugia tune** with hard $P_T > 10$ GeV

→ PYTHIA **embedded** into real zero-bias pp events



Data sample

- **pp – transverse** (collected in 2011) @ √500 GeV
- Integrated luminosity: **~ 25 pb^{-1}**
- Events triggered in Barrel EMCAL

Signal

$W \rightarrow e\nu_e$

Background

$W \rightarrow t\nu_t \rightarrow e\nu_e\nu_t$

$Z \rightarrow ee$

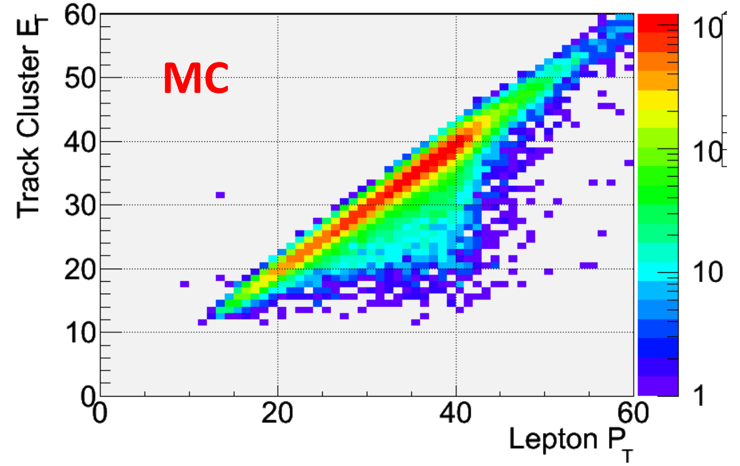
QCD events

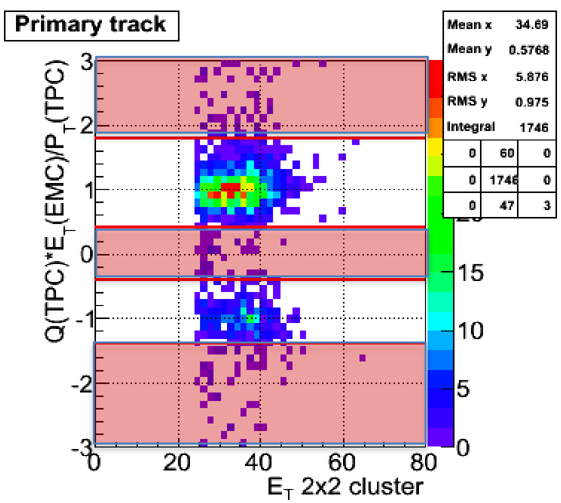
Electron identification

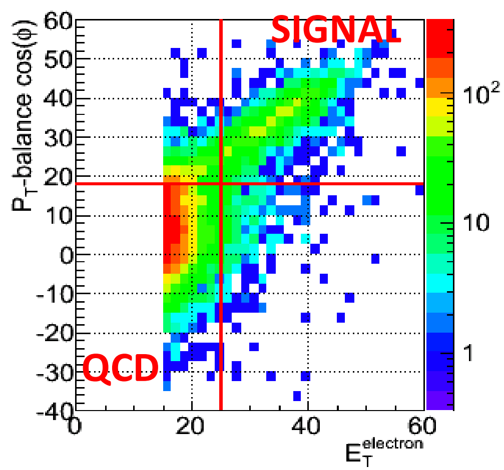
- **Isolation:** $(P^{track}+E^{cluster}) / \Sigma[P^{tracks}$ in R=0.7 cone] > 0.8
- **Imbalance:** no energy in opposite cone (E<20 GeV)
- **E_T > 25 GeV**
- Track |η| < 1
- |Z-vertex|<100 cm
- **Charge separation** (avoids charge misidentification):

  0.4 < |Charge (TPC) x E_T (EMC) / P_T (TPC)| < 1.8
- Signed P_T balance > 18 GeV/c (**rejects QCD Background**)
- 0.5 GeV/c < P_T^W < 10 GeV /c

We calculate energy from the cluster







$$\vec{P}_T^{\,bal} = \vec{P}_T^{\,e} + \sum \vec{P}_T^{\,recoil}$$

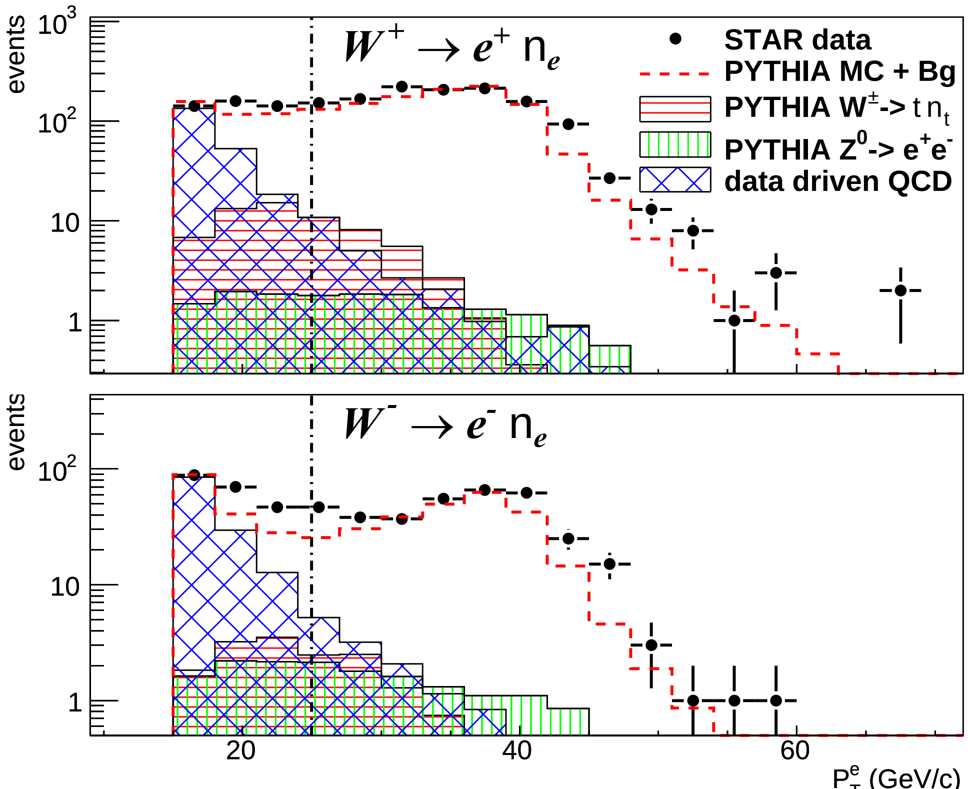
Background estimation

Background from W and Z boson decays estimated via Monte Carlo

- **PYTHIA 6.4 with Perugia 0 tune**
- **normalized to recorded data luminosity**

Data-driven QCD background estimation

- **Reverse of P_T-balance cut [PT-balance < 15 GeV] → Selects QCD events**
- **Plot lepton-P_T > 15 GeV**
- **QCD sample normalized to the first P_T-bin [15-19 GeV]**



- Positive-charge signal **1016 events**
- $Z^0 \to ee$ **[B/S = 0.79% ± 0.03%]**
- $W^+ \to \tau\nu_\tau$ **[B/S = 1.89% ± 0.04%]**
- ***QCD*** **[B/S = 1.6% ± 0.09%]**

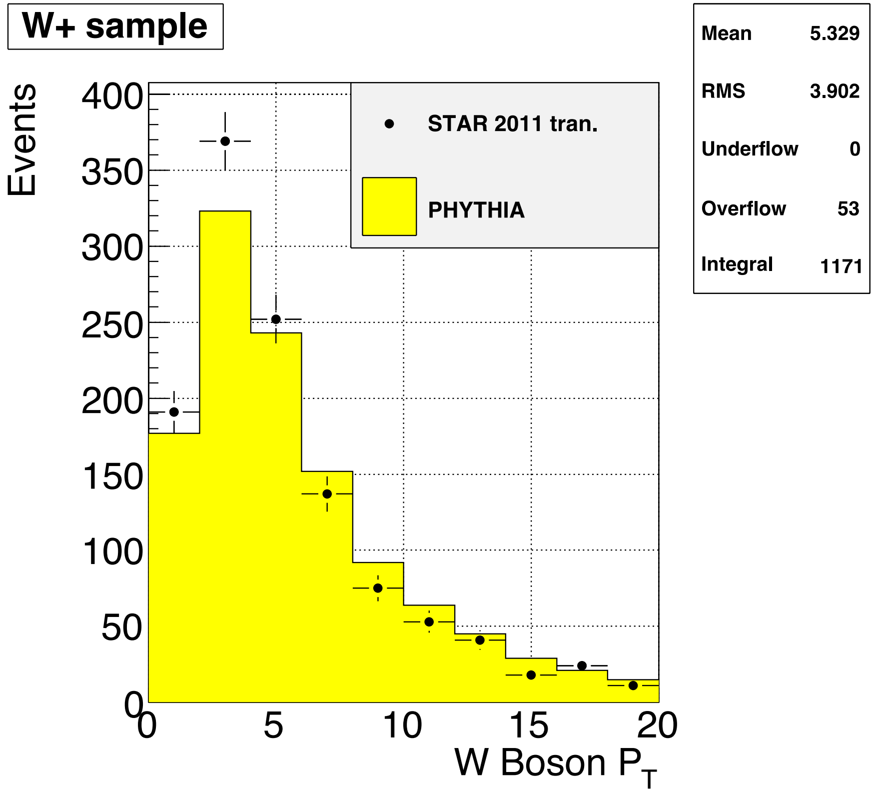
- Negative-charge signal **275 events**
- $Z^0 \to ee$ **[B/S = 2.67% ± 0.1%]**
- $W^- \to \tau\nu_\tau$ **[B/S = 1.77% ± 0.1%]**
- ***QCD*** **[B/S = 3.39% ± 0.23%]**

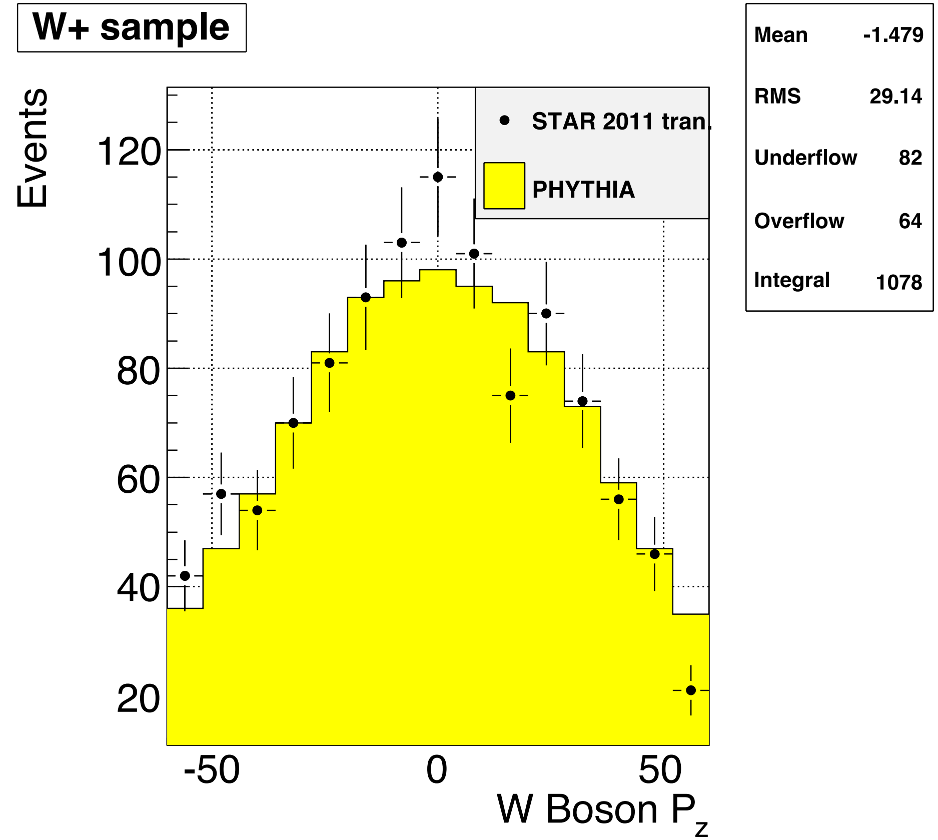
Backgrounds under control!

W P_T – Data/MC

We add to our selection:

- Track-P_T in the recoil > 0.2 GeV
- Total recoil-P_T > 0.5 GeV





GOOD data/MC agreement after P_T correction

Summary table

	$A_N(W^{+/-},Z^0)$	$A_N(DY)$	$A_N(\gamma)$
sensitive to sign change through TMDs	yes	yes	no
sensitive to sign change through Twist-3 $T_{q,F}(x,x)$	no	no	yes
sensitive to TMD evolution	yes	yes	no
sensitive to sea-quark Sivers fct.	yes	yes	no
need detector upgrades	no	yes at minimum: FMS postshower	yes pre-showers installed for run-15
biggest experimental challenge	integrated luminosity	background suppression & integrated luminosity	need to still proof analysis on data

$A_N(W^{+/-},Z^0)$ clean probe sensitive to all questions without the need for upgrades